Plasma Astrophysics and Modern Plasma Cosmology Postprint

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Abstract

Modern science indicates that over 99% of observable matter in the universe exists in the plasma state. From small-scale collective processes of microscopic particle dynamics and energy conversion mechanisms to large-scale states of cosmic plasma astrophysical structures and eruptive activity phenomena, all constitute research topics of plasma astrophysics. This work systematically discusses the important role of plasma astrophysics in the development of modern astronomy and the formation of a modern plasma cosmological perspective, from the perspectives of cosmic evolution history, large-scale structure formation, and eruptive activity phenomena. Simultaneously, in conjunction with space satellite scientific exploration research and its tremendous impact on modern astronomy, it further elaborates on the unique role of in-situ space plasma detection research in Earth' s magnetosphere and heliosphere as a "natural laboratory' ' for plasma astrophysics.

Full Text

Plasma Astrophysics and Modern Plasma Cosmology

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Abstract

Modern science shows that more than 99% of observable matter in the universe exists in a plasma state. Plasma astrophysics investigates phenomena ranging from small-scale collective processes in particle kinetics and energy conversion mechanisms to large-scale structures of cosmic plasma objects and their eruptive activities. This paper systematically discusses the crucial role of plasma astrophysics in modern astronomy and the formation of a modern plasma cosmology, covering cosmic evolution history, large-scale structure formation, and eruptive phenomena. Additionally, considering the tremendous impact of space satellite scientific exploration on modern astronomy, we further elaborate on the unique function of in-situ space plasma detection studies of Earth' s magnetosphere and heliosphere as a "natural laboratory" for plasma astrophysics research.

Keywords: Big Bang cosmology, large-scale structure of the universe, high-energy astrophysics: eruptive activities of objects, plasma astrophysics, cosmology: plasma cosmology

1 Introduction: Why Modern Astronomy Needs Plasma Astrophysics

Astronomy is an ancient discipline built upon observational foundations. Modern scientific astronomy began in 1609 when Galileo pointed his first telescope skyward, discovering not only far more stars than previously visible to the naked eye but also revealing lunar topography, Venus' s phases, Jupiter' s moons, Saturn' s rings, and many previously unknown phenomena, thus ushering in a new era of modern astronomy. The combination of 17th-18th century astronomical observations with Newtonian mechanics gave birth to celestial mechanics, while 19th-20th century spectroscopic observations combined with atomic physics further produced astrophysics. As an observational science, astronomy can theoretically obtain physical information about celestial bodies through four channels: electromagnetic radiation, cosmic rays, neutrinos, and gravitational waves [**?**]. However, due to enormous difficulties in detecting neutrino and gravitational wave signals, the only truly valuable information channels are electromagnetic radiation and cosmic ray particles. Although both neutrinos and gravitational waves have been directly detected, with related results winning multiple Nobel Prizes in Physics (gravitational waves in 1993 and 2017; neutrinos in 1988, 1995, 2002, and 2015), the information content is extremely limited and largely consists of isolated cases, making it difficult to provide effective information for sustained research. Consequently, over 90% of astrophysical information still comes from observations of electromagnetic radiation from various celestial bodies, and the fundamental task of astrophysics is to analyze and interpret the electromagnetic spectra of celestial objects and thereby establish physical models of their structure and evolution. Therefore, the development of astrophysics has been driven forward alongside the advancement of electromagnetic waveband observational technology.

The electromagnetic spectrum spans about 20 orders of magnitude in wavelength, from low-frequency radio waves to high-energy gamma rays. However, until the 1940s, astronomy could effectively utilize only the visible light window covering wavelengths of 0.4–0.8 μm—a mere half-order-of-magnitude range. Nevertheless, within less than a century, astrophysics based on optical observations achieved tremendous accomplishments, including establishing stellar atmosphere models centered on visible light radiative transfer theory, stellar structure and evolution models centered on thermonuclear fusion, and cosmic evolution models centered on the Hubble expansion concept. Since the end of World War II, however, astronomical observation technology has achieved major breakthroughs in two directions: first, the development of radar technology opened up broader radio wave detection windows [**?**]; second, space satellite technology enabled space-based astronomical observations, eliminating atmospheric absorption and turbulence effects and further opening high-energy observation windows in X-rays and gamma rays [**?**].

These two major breakthroughs in observational technology not only gave rise to new branches of astronomy such as radio astronomy and X-ray astronomy but also revealed an unprecedented picture of cosmic matter distribution and structure, greatly expanding the horizons of astrophysical research. Simultaneously, they caused a major shift in astrophysical research direction, from studying stable celestial bodies and systems with stable orbits and shapes (such as stars, galaxies, and galaxy clusters) and their long-term evolution in quasi-static equilibrium, to investigating diffuse cosmic plasma objects (such as interstellar medium, intergalactic medium, and hot gas in galaxy clusters) and non-stationary eruptive phenomena (such as solar flares, supernova explosions, extragalactic radio jets, gamma-ray bursts, and fast radio bursts) and their transient dynamical processes. The former is dominated by gravitational interactions, while in the latter, electromagnetic interactions between plasma objects and magnetic fields play crucial roles. It is precisely the combination of all-waveband astronomical observations—especially radio and X-ray astronomy —with plasma physics that has led to the birth of a new interdisciplinary field: plasma astrophysics.

Meanwhile, with the advent of the human space age, in-situ space satellite detection has revealed increasingly rich multi-scale structural phenomena and dynamical evolution processes of natural cosmic plasmas. Examples include the complex Earth' s magnetosphere and its global current coupling system, large-scale magnetic plasma structures in the heliosphere, various magnetic neutral current sheets, current-carrying magnetic flux tubes, nonlinear solitary wave structures, collisionless shocks, magnetic reconnection, particle acceleration, and ubiquitous plasma wave turbulence. What we can directly observe through astronomical observations are electromagnetic waves from distant celestial bodies, which are merely byproducts of a series of complex magnetic plasma dynamical processes occurring in those distant objects: electromagnetic radiation produced by accelerated charged particles. However, many natural cosmic plasmas do not directly produce observable electromagnetic radiation, making it impossible to gain deep understanding of their structural states and dynamical processes through traditional astronomical observations of electromagnetic waves. The in-situ detection results from space satellites undoubtedly provide us with practical opportunities to deeply understand the dynamical processes of natural cosmic plasmas and offer a "natural laboratory" for further in-depth research in plasma astrophysics.

Modern science shows that more than 99% of observable matter in the universe is in a plasma state, where long-range electromagnetic forces not only dominate particle micro-dynamical processes but also constitute crucial factors in the formation of large-scale cosmic structures and their macro-dynamical evolution. This paper systematically elucidates the essential role of plasma astrophysics in modern astronomy and the formation of a plasma cosmology from several perspectives: cosmic evolution history (Section 2), large-scale structure states of cosmic plasma objects (Section 3), and cosmic eruptive phenomena and their energy conversion mechanisms (Section 4). Additionally, combined with abundant results from space satellite detection, we further elaborate on the unique function of in-situ space plasma detection research as a natural laboratory in plasma astrophysics (Section 5). Finally, we provide a brief summary and outlook for the disciplinary development direction and future trends of plasma astrophysics (Section 6).

2 Cosmic Expansion History: From Primordial Plasma Fireball to Reionized Plasma Universe

Although the Big Bang cosmological model contains many unsolved mysteries, it has become the most widely accepted standard cosmological model due to strong support from three major observational phenomena: cosmic expansion, cosmic microwave background radiation, and cosmic element abundances. According to the Big Bang model, the currently observed universe began with a singular Big Bang over 10 billion years ago. Before the Planck time $t_p \sim 5.38 \times 10^{-44}$ s after the initial explosion, the universe existed in a singular state beyond the descriptive scope of modern physical theory. The so-called Planck time refers to the shortest time required to establish physical causal connections within the smallest black hole. Based on the uncertainty principle of modern quantum theory, the smallest experimentally determinable black hole radius is approximately $r_s \sim 2l_p \sim 3.23 \times 10^{-35}$ m ($l_p \sim 1.61 \times 10^{-35}$ m is the Planck length), with a corresponding minimum black hole mass—the Planck mass—of $M_p \sim 2.18 \times 10^{-8}$ kg. Black holes are the most compact objects in the universe, with average density decreasing as radius increases. Therefore, the highest determinable density, the Planck density, is that of this minimum black hole: $\rho_p \sim 3M_p/(4\pi r_s^3) \sim 1.55 \times 10^{95}$ kg/m^3, with corresponding energy density $\epsilon_p \sim \rho_p c^2 \sim 1.39 \times 10^{112}$ J/m^3, or radiation thermal equilibrium temperature $T_p \sim 10^{32}$ K $\sim 10^{19}$ GeV [?].

Based on estimates that the total mass within the currently observable universe is about $M_0 \sim 10^{52}$ kg, and assuming conservation of total matter during cosmic expansion, the cosmic scale at the Planck epoch should have been $R_p \sim 2.49 \times 10^{-15}$ m. Establishing physical causal connections would require a "long" time of $\sim 10^{-23}$ s. To overcome this causality difficulty, Guth proposed the cosmic inflation model in the early 1980s [?], suggesting that the dense "energy packet" of the universe from the Planck time experienced a "slow" expansion until $t \sim 10^{-35}$ s, when the cosmic density decreased to $\sim 10^{79}$ kg/m^3 and temperature dropped to $T \sim 10^{28}$ K $\sim 10^{15}$ GeV. At this point, the vacuum Higgs field with negative pressure began to dominate, causing the universe to undergo an inflationary phase that expanded its scale by $\sim 10^{26}$ times within $t \sim 10^{-34}$ s. During this period, cosmic density and temperature did not decrease by the "expected" factors of $\sim 10^{78}$ and $\sim 10^{19.5}$, respectively, but remained almost constant due to continuous replenishment and reheating from the vacuum Higgs field. Therefore, at the end of the inflationary phase, most of the matter in the observable universe did not come from the primordial "energy packet" of the Planck era but from the continuous replenishment of the vacuum Higgs field during inflation. Thereafter, cosmic evolution entered the so-called "Grand Unified Theory (GUT)" era of particle interactions, where strong, weak, and electromagnetic interactions were of comparable magnitude. However, particle production processes during this period remain experimentally unverifiable, as both current laboratory high-energy particle accelerators and high-energy cosmic ray observations have energies below 10^{14} GeV [**?**]. Here, we provide a brief description of the physical states of cosmic energy and matter during various evolutionary epochs after inflation, which represent the main states that matter in the currently observable universe has experienced during cosmic evolution.

2.1 Quark-Gluon Plasma Epoch ($t \sim 10^{-34}$-10^{-5} s, $T \sim 10^{28}$-10^{12} K)

After the inflationary phase ended, the universe began adiabatic expansion that continues to the present day. According to modern quantum field theory's Grand Unified Theory, in the early stages of cosmic adiabatic expansion, cosmic matter mainly consisted of six types of quarks with fractional charges (top, charm, and up quarks with charge $+(2/3)e$, and bottom, strange, and down quarks with charge $-(1/3)e$) and corresponding antiparticles with opposite charges. Due to extremely high temperatures, these quarks could exist as free-moving particles and interact strongly through gluon exchange. Simultaneously, they reached thermal equilibrium with the radiation field through annihilation and pair production of particles and antiparticles. Therefore, the early universe at this time was actually in an extremely high-temperature plasma state called "quark-gluon plasma." Additionally, the quark-gluon plasma contained a small mixture of leptons and corresponding antileptons. There are six types of leptons: tau, muon, electron, and their corresponding neutrinos. The tau and muon, like the electron, carry charge $-e$, but all three types of neutrinos are neutral. These quarks and leptons are the most fundamental particles in the modern particle physics framework that constitute all existing matter in the universe, and the early hot cosmic evolution stage was composed of these basic particles and their antiparticles in an extremely high-temperature quark-gluon plasma.

Around $t \sim 10^{-10}$ s, when the cosmic temperature dropped to $T \sim 2 \times 10^{15}$ K $\sim$ 175 GeV, the heaviest top quark (mass $\sim$ 172 GeV) began to annihilate into radiation energy and transform into lighter quarks. When the temperature fell to $T \sim 2\times10^{13}$ K, the heaviest lepton (the tau with mass $\sim$ 1.78 GeV) also began to annihilate into radiation energy. By $t \sim 10^{-5}$ s, when the temperature further decreased to $T \sim 3\times10^{12}$ K $\sim$ 250 MeV, bottom and charm quarks with masses of $\sim$ 4.19 GeV and 1.27 GeV, respectively, also disappeared from the universe through successive annihilation. Meanwhile, the corresponding cosmic matter density decreased to $\rho \sim 3 \times 10^{17}$ kg/m^3, comparable to the current baryon (proton, neutron) mass density $\rho_b \sim 4 \times 10^{17}$ kg/m^3. Baryons with zero net color charge consist of three quarks coupled through strong interactions, where protons are composed of "up-up-down" quarks with charge $+e$, and neutrons are composed of "down-down-up" quarks with total charge zero. The characteristic scale of strong interactions, i.e., the characteristic radius of baryons, is $r_b \sim 10^{-15}$ m, with corresponding baryon binding energy of about 300 MeV. As cosmic expansion continued and the temperature dropped to the binding energy for quark combination, reaching the freeze-out temperature of the quark-gluon plasma, a cosmic phase transition from quark-gluon plasma to baryon-lepton plasma occurred. At this point, the surviving up and down quarks from quark-gluon plasma annihilation were no longer in free thermal motion but became "confined" within the baryon scale of $r_b \sim 10^{-15}$ m through strong interaction coupling to form stable protons and neutrons. Since then, the state of cosmic matter has evolved from the quark-gluon plasma era into the "baryon-lepton plasma epoch" [**?**].

2.2 Baryon-Lepton Plasma Epoch ($t \sim 10^{-5}$-10^2 s, $T \sim 10^{12}$-10^9 K)

During the cosmic evolution from quark-gluon plasma to baryon-lepton plasma, the main components of cosmic matter were baryons, leptons, and their corresponding antiparticles, with electromagnetic forces playing the dominant role. However, in this universe dominated by matter-antimatter components, a troubling problem is the asymmetry between particles and antiparticles. According to the above cosmic evolution picture, particles and antiparticles in the early universe should have been produced and annihilated in pairs, so the numbers of baryons and antibaryons in the present universe should be roughly equal. However, cosmic ray observations show that the number of antiparticles in various energy ranges is only on the order of a few per million to a few per ten thousand, and these tiny amounts of antiparticles might be produced in collisions between high-energy cosmic rays and interstellar medium [**?**, **?**]. Of course, based on astronomical observations alone, it is indeed difficult to distinguish whether distant celestial bodies might be composed of antiparticles, because atoms and molecules made of particles and antiparticles have completely identical internal electromagnetic structures and thus identical spectral characteristics. However, when particle-composed and antiparticle-composed celestial bodies approach each other, high-energy gamma-ray radiation from particle-antiparticle annihilation would inevitably be produced at their boundaries. Yet, no clear evidence of such annihilation radiation has been observed for a long time. Therefore, we have to accept the conclusion that the existing matter in the universe is mainly composed of particles.

As for the origin of the particle-antiparticle asymmetry, one possible explanation attributes it to parity violation in weak interactions. In current particle theory, the three types of neutrinos that only participate in weak interactions have mass upper limits below 1 eV (or zero mass). However, some very massive neutrinos might have existed in the early universe' s quark-gluon plasma. At $t \sim 10^{-11}$ s, before top quarks began to annihilate, the cosmic temperature was about $T \sim 3.4 \times 10^{15}$ K $\sim$ 300 GeV. These massive neutrinos decayed through weak interactions, producing particles and antiparticles that exhibited weak asymmetric fluctuations due to parity violation. The result was a slight excess of lepton number (the difference between lepton and antilepton numbers), accounting for about 10^{-9} of the total lepton number. Meanwhile, according to the requirements of electromagnetic interaction gauge invariance, as compensation for charge conservation, the quark-gluon plasma would also produce strictly equal "fluctuations" in baryon number (the difference between baryon and antibaryon numbers). Thereafter, as the universe expanded and cooled, most particle-antiparticle pairs annihilated into radiation energy and merged into the cosmic background radiation, leaving only a tiny amount of residual matter particles that constitute all the matter components in the currently observable universe. Based on observations of the present cosmic baryon-to-photon ratio, only 10^{-9}-level asymmetric fluctuations in the decay of particles and antiparticles would be sufficient to explain the huge asymmetry between matter and antimatter in the current universe [**?**].

With cosmic evolution entering the baryon-lepton plasma era, in addition to a large number of relatively stable baryon and antibaryon particles, there were also many unstable particles such as pions and anti-pions formed by quark-antiquark pairs. These unstable mesons seem to mainly serve as an intermediary for converting cosmic energy from quarks to leptons, because once formed, they would annihilate to release photons, electrons, positrons, neutrinos, and antineutrinos, heating these cosmic components. Additionally, there were extremely small amounts (about 10^{-9} of the total baryon number) of residual protons and neutrons resulting from parity-violating fluctuations. When cosmic evolution reached $t \sim 0.01$ s and the temperature further dropped to below $T \sim 10^{11}$ K, the residual protons and neutrons reached thermal equilibrium through interactions with background electrons, positrons, electron neutrinos, and antineutrinos. The neutron-to-proton ratio could be determined by the mass difference between neutrons and protons through the Boltzmann distribution and decreased with decreasing cosmic temperature. By $t \sim 0.1$ s, when the temperature further dropped to $T \sim 3 \times 10^{10}$ K, the rate of weak interactions became slower than the cosmic expansion rate, causing neutrinos, which only participate in weak interactions, to decouple from other particles. The main thermal equilibrium process in the universe became the balance between electron-positron pairs and radiation photons. When $t \sim 1$ s and $T \sim 10^{10}$ K, the cosmic background was insufficient to maintain reaction equilibrium between protons and neutrons, so the neutron-proton abundance ratio also froze at the Boltzmann equilibrium value at this time, approximately 1:5 [**?**]. This abundance ratio also determined the cosmic helium-to-hydrogen abundance ratio formed in the subsequent primordial nucleosynthesis process. The balance between electron-positron pair annihilation and production would be broken at a cosmic temperature of $T \sim 3 \times 10^9$ K, when cosmic evolution had progressed to $t \sim 10$ s. Thereafter, a large number of electron-positron pairs annihilated into radiation photons and merged into the cosmic background radiation. A small number of residual electrons (about 10^{-9} of the total electron number) caused by asymmetric fluctuations from neutrino decay survived to this day and later combined with protons in cosmic evolution to form hydrogen atoms, the main component of observable cosmic matter.

2.3 Proton-Electron Plasma Epoch ($t \sim 10^2$-10^{13} s, $T \sim 10^9$-10^3 K)

When cosmic evolution progressed to $t \sim 100$ s, the cosmic temperature had already dropped to $T \sim 10^9$ K. Most particle-antiparticle pairs had essentially annihilated into photons, leaving only tiny amounts (about 10^{-9}) of residual electrons, protons, and neutrons, with electron and proton numbers being comparable. It was these residual matter particles that constitute all currently observable cosmic matter and are regarded as "normal" particles. Cosmic evolution entered the "proton-electron plasma epoch" dominated by positive matter components, with electromagnetic forces remaining the dominant interaction between matter particles. Subsequently, starting from about $t \sim 120$ s and temperature $T \sim 0.9 \times 10^9$ K, protons and neutrons began to combine to form deuterium nuclei, which then rapidly generated more stable helium nuclei (alpha particles) through nuclear reactions until all neutrons were exhausted. This nucleosynthesis lasted only a few minutes. Due to cosmic expansion and cooling, helium nuclei could no longer generate heavier elements through nuclear reactions. By $t \sim 10^3$ s and temperature $T \sim 3 \times 10^8$ K, the initial cosmic element abundances were basically determined. Due to the unstable decay of neutrons (half-life $\tau \sim 600$ s) producing protons and electrons, the neutron-to-proton ratio at the beginning of nucleosynthesis was about 1:7. When nucleosynthesis ended and neutrons were exhausted, the ratio of helium nuclei to protons was about 1:12, corresponding to a helium abundance of $\sim 25\%$ [**?**].

The subsequent cosmic evolution entered a relatively gentle and long-lasting phase. Around $t \sim 10^{11}$ s, the cosmic temperature had decreased to about 10^5 K, below the ionization potential of hydrogen atoms (~ 13.6 eV). Hydrogen nuclei (protons) and helium nuclei (alpha particles) could then capture free electrons to form stable neutral hydrogen and helium atoms, and cosmic evolution entered the "recombination epoch." This recombination period lasted until $t \sim 10^{13}$ s and temperature ~ 3000 K, when most protons and helium nuclei had combined with electrons to form neutral hydrogen and helium atoms. Meanwhile, as the recombination epoch progressed, the universe' s primordial electromagnetic radiation gradually decoupled from the material particle components because it could not effectively interact electromagnetically with neutral atoms. During this period, the universe transitioned from a radiation-dominated state to a matter-dominated state, where the energy density of matter particles exceeded that of electromagnetic radiation [**?**]. The decoupled cosmic radiation has persisted to this day as the cosmic microwave background radiation discovered by Penzias and Wilson in 1965 [**?**], though its temperature has cooled to only about 2.7 K due to cosmic expansion.

In the quark-gluon and baryon-lepton plasma epochs, the main components of cosmic matter were particle-antiparticle plasmas, and the dominant physical processes were annihilation and production of particle-antiparticle pairs. In the proton-electron plasma epoch, the main components were protons, neutrons, and electrons. These positive matter particles, which constitute all currently observable cosmic matter, were trace amounts of residual positive matter produced by weak asymmetric fluctuations due to parity symmetry breaking during early cosmic evolution. They gradually became the dominant components of cosmic matter only after all particle-antiparticle pairs had annihilated.

2.4 Neutral Hydrogen-Helium Gas Epoch ($t \sim 10^{13}$-10^{16} s, $T \sim 10^3$-10 K)

Thereafter, the cosmic neutral gas composed mainly of hydrogen and helium atoms, under the action of gravity through the development of Jeans instability, began to form the first generation of stars around $t \sim 10^{16}$ s (when the cosmic temperature had dropped to about 10 K), and subsequently formed galaxies, galaxy clusters, and other large-scale structures, as well as star-planet systems containing numerous small bodies. During this process, the main component of cosmic matter was neutral hydrogen gas, and the dominant interaction between cosmic matter particles was gravity.

However, if large-scale magnetic fields could be effectively formed during the proton-electron plasma epoch and survive after the recombination epoch, long-range electromagnetic forces would still have the opportunity to participate in the formation of the first generation of celestial bodies at various scales. Modern astronomical observations show that magnetic fields indeed exist at various scales from planets and stars to galaxies and galaxy clusters. The origin of these magnetic fields has always been a major unsolved problem—the so-called cosmic magnetic field origin problem. Whether through cosmological origins accompanying the primordial Big Bang or astrophysical origins accompanying celestial body formation, the ubiquitous presence of these magnetic fields would likely play important roles in the formation of cosmic plasma structures. For example, Alfvén pointed out in his studies of solar system evolution: when neutral atoms accelerate gravitationally toward a gravitational center, if their kinetic energy reaches the magnitude of their ionization potential, they may become ionized when crossing magnetic fields and be blocked by the Lorentz force of the magnetic field, a phenomenon called the “critical ionization velocity phenomenon.” Using this critical ionization velocity phenomenon, Alfvén successfully explained the banded structure of planet and satellite formation and distribution in the solar system [**?**].

2.5 Reionization Plasma Epoch ($t \sim 10^{16}$ s-present, $T \sim 10$-2.7 K)

After the birth of the first generation of stars, neutral gas inside and outside stars returned to a plasma state through thermonuclear fusion and photoionization processes, generally called the cosmic reionization process. The corresponding cosmic evolutionary stage is also called the "cosmic reionization plasma epoch." After entering the reionization evolutionary epoch, cosmic plasma objects, in addition to the original proton-electron plasma (i.e., ionized hydrogen plasma), also included heavy elements such as iron, oxygen, carbon, and nitrogen formed by thermonuclear fusion inside stars. These elements were ejected into surrounding cosmic space in the form of supernova explosions at the end of stellar evolution, serving as raw materials for supernova remnants and the next generation of star formation. Therefore, after reionization, observable cosmic matter still mainly presents as plasma objects, with electromagnetic forces again playing important or even dominant roles in the interaction processes of cosmic matter. Through the combined action of gravity and electromagnetic forces, various types of plasma objects and their eruptive activity phenomena observed today were formed. These plasma objects now occupy more than 99% of observable cosmic matter. Compared with pre-recombination cosmic plasma, important changes have occurred in both composition and structure, manifested not only as complex plasmas with multiple ion components but also as complex non-uniform magnetic plasma structures and violent electrodynamical evolution.

During this epoch, the distribution of cosmic matter exhibits local non-uniformities at various scales from planets and stars to galaxies and galaxy clusters, with gravity and gravitational potential energy playing major roles in the formation and dynamical evolution of these non-uniform structures. Meanwhile, in the non-uniform potential field environment near gravitational centers, collisionless plasma electrons and ions, due to their different force states, will produce relative separation and drift motions, leading to the formation of large-scale macroscopic charge and current distributions. In interstellar media far from gravitational centers, electromagnetic forces can even far exceed gravity and dominate the dynamical structure and behavior of interstellar plasma media. For example, in the solar corona, the macroscopic electric force on protons can reach half of gravity, while the electric force on electrons far exceeds gravity. In interplanetary space far from the Sun, even the electromagnetic force on protons can far exceed their gravitational force. Although the microscopic electrostatic Coulomb force in plasma dynamics can "bind" the main components of electrons and ions tightly together, it cannot completely "smooth out" macroscopic charge and current separation phenomena. Additionally, due to the electromagnetic properties of cosmic matter in the plasma state, under the combined action of gravity and electromagnetic forces, cosmic plasma objects in various non-uniform structures can spontaneously establish plasma current circuit systems and effectively convert gravitational energy into electromagnetic energy stored in these current systems. The electrodynamical evolution of these plasma current circuit systems and their stored free electromagnetic energy constitute the most important and universal driving source for various cosmic eruptive activity phenomena.

summarizes the main matter components and physical processes during different epochs of cosmic evolution. Looking at the evolutionary history of the Big Bang cosmological model, after the brief inflationary period following the primordial singular Big Bang, the state of cosmic matter has been dominated by plasma. The early hot universe was mainly composed of quark-gluon plasma. As the universe expanded and cooled, reaching the freeze-out temperature of quark-gluon plasma at $T \sim 300$ MeV ($t \sim 10^{-5}$ s), quarks became confined by strong interactions within a scale of $r_b \sim 10^{-15}$ m to form stable baryons—protons and neutrons—and the state of cosmic matter transformed into baryon-lepton plasma. The main particle components of cosmic plasma during these two epochs existed in the form of matter-antimatter particle pairs. In subsequent cosmic evolution, as temperatures further decreased, large numbers of particle-antiparticle pairs successively annihilated into radiation photons. The released energy partially heated the residual matter particles and partially merged into the cosmic background radiation field, becoming components of the currently observed cosmic microwave background radiation. The weak asymmetry (only about 10^{-9}) between matter and antimatter caused by initial parity symmetry breaking survived after particle-antiparticle annihilation to compose proton-electron plasma, which gradually became the main component of cosmic matter as evolution proceeded. After experiencing recombination and forming various celestial bodies such as stars, galaxies, and galaxy clusters under gravity, these proton-electron plasmas underwent reionization to become the reionized plasma or complex plasma objects that now occupy the overwhelming majority of observable cosmic matter. These complex plasma objects, through the combined action of long-range electromagnetic forces and gravity, constitute various plasma objects at different scales, presenting rich types of celestial structures and eruptive activity phenomena. Therefore, plasma and its electromagnetic interactions must play essential and even dominant roles in the structural formation and evolution of cosmic matter. This is not only because electromagnetic force is a long-range force like gravity, but more importantly because electromagnetic force is a long-range force 10^{36} times stronger than gravity. In Sections 3 and 4, we will further elaborate on the research content of plasma astrophysics and its important role in modern astronomical research based on the distribution and structural characteristics of cosmic plasma objects and their eruptive activity phenomena revealed by modern astronomical observations.

3 Modern Astronomical Observations of Cosmic Plasma Objects and Their Large-Scale Structural Characteristics

In the era of optical astronomy, the celestial bodies that could be directly observed were stars and systems composed of stars, such as galaxies and galaxy clusters. The direct radiation source of stellar visible light is mainly the very thin photosphere on the stellar surface (for example, the thickness of the Sun' s photosphere is less than one-thousandth of the solar radius), whose mass accounts for only an extremely negligible fraction of the stellar mass (the mass of the Sun' s photosphere is about one ten-millionth of the solar mass). The photosphere is also the coolest part of the entire star, typically several thousand to ten thousand degrees, with neutral hydrogen as the main component, generally in local thermodynamic equilibrium. Radiation photons mainly originate from hydrogen atomic transition radiation, and the radiation spectrum appears as an almost constant blackbody spectrum in thermal equilibrium. Below the photosphere, temperature gradually increases toward the stellar center, reaching tens of millions of degrees at the center and forming a huge plasma thermonuclear fusion reactor. Above the photosphere, temperature also gradually increases outward, reaching millions of degrees, forming an extensive high-temperature plasma stellar corona that accelerates outward to form a stellar wind blowing into interstellar space. Therefore, except for the coolest photosphere on the surface, the entire star is almost in a plasma state, making it a typical plasma object. Inside the photosphere is high-temperature dense plasma constrained by gravity, forming a thermonuclear fusion reactor in the core that continuously transports stellar radiation energy outward in the form of high-energy photons, while the exterior is an extended atmosphere filled with high-temperature tenuous plasma—the stellar corona and stellar wind.

3.1 Radio Observations of Cosmic Plasma Objects

For a long time, human understanding of the vast cosmic space beyond stars was limited, because interstellar and intergalactic media diffused in interstellar space are "invisible" in the visible light band. As plasmas, their main electromagnetic radiation is in the radio and X-ray bands. Therefore, when observation windows in other electromagnetic bands, especially radio and X-ray bands, were opened, a completely new cosmic picture was presented before us. In fact, as early as 1890, two years after electromagnetic wave propagation was confirmed in laboratories, suggestions were made to observe radio radiation from the Sun. However, due to detection technology limitations, early efforts were unsuccessful. It was not until 1931 that Jansky, a young telecommunications engineer at Bell Telephone Laboratories in the United States, discovered an extraterrestrial radio radiation signal from the direction of the Galactic center at a wavelength of 14.6 m through one year of monitoring using a direction-sensitive antenna array. Subsequently, another American amateur astronomer, Reber, further improved upon Jansky' s observations, detecting radio signals from the same direction at a shorter wavelength of 1.87 m, and published the results in the professional American astrophysics journal ApJ, bringing Jansky' s early observational achievements to the deserved attention of the astronomical community [?]. Consequently, the term "Jansky" was officially adopted in 1973 as the unit of celestial radio radiation flux and incorporated into the International System of Physical Units: $1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W \cdot m^{-2} \cdot Hz^{-1}}$. The reason for defining such a low radio flux unit is that in the solar system' s cosmic environment, the celestial radio signals we receive are extremely weak, while stronger radio radiation sources come from very distant active celestial bodies. Therefore, radio telescopes can be called the most sensitive detection instruments in the world. Only in the second half of the last century, driven by the high-sensitivity, high-detection-efficiency radar technology developed during wartime, did radio astronomy truly begin to develop rapidly and achieve tremendous accomplishments. For example, the four major astronomical discoveries of the 1960s—quasars, pulsars, cosmic microwave background radiation, and interstellar molecular masers—are all closely related to radio astronomy.

Within the solar system, radio radiation is the most common plasma object electromagnetic radiation phenomenon. From solar radio bursts, planetary magnetosphere radio radiation, to interplanetary radio bursts and solar wind-interstellar medium interaction boundary layer radiation, radio radiation sources exist in almost every heliospheric region from the Sun to the heliospheric boundary layer. The radio radiation band also covers a wavelength range of eight orders of magnitude from $\sim 10^5$ m (solar system boundary layer radiation) to $\sim 10^{-3}$ m (solar lower atmosphere). Moreover, observations show that these radio bursts often accompany violent magnetic plasma activity phenomena such as solar flares, coronal mass ejections, and planetary magnetosphere magnetic storms. Theoretical studies of radiation mechanisms further indicate that these radio bursts are collective coherent radiation excited by non-thermal high-energy electron beams through plasma instabilities, with very significant non-thermal high-energy characteristics. Considering that the solar system is only an extremely ordinary normal star system in the Milky Way, we have reason to believe that non-thermal radio radiation phenomena from magnetic plasma objects must exist throughout all regions of the universe and are the most universal plasma object electromagnetic radiation phenomena, closely related to the accumulation and release of electromagnetic energy in plasma objects.

Unlike the thermal equilibrium blackbody spectrum of stellar optical radiation, on larger scales, the radio radiation spectra of cosmic objects (except for the cosmic microwave background radiation spectrum) often exhibit significant non-thermal power-law spectral characteristics. In particular, the most powerful radio galaxies often show extended radio jets and radio lobe structures reaching millions of light-years. These structures are not only far larger in spatial scale than ordinary galaxies, reaching the order of galaxy cluster scales, but also have radio radiation luminosities 10^3-10^6 times higher than their optical luminosities, with radiation powers as high as 10^{43}-10^{45} erg/s [**?**, **?**]. Further theoretical studies of radiation mechanisms show that these powerful radio radiations are mainly produced by relativistic non-thermal high-energy electrons with power-law energy spectra through magnetic bremsstrahlung in magnetic fields. This implies that these large-scale extended radio source regions must be filled with very active high-energy plasma object components that continuously release enormous energy to provide the driving energy source for accelerating non-thermal high-energy electrons, and the interaction between magnetic fields and plasma and its current systems must play important roles. In particular, the formation of typical non-spherically symmetric large-scale structures like radio jets and radio lobes is obviously a non-gravity-dominated process. Cosmic large-scale magnetic fields and their long-range electromagnetic forces must play a key dominant role in the formation and macro-dynamical evolution of these large-scale structures [**?**, **?**, **?**, **?**]. Later X-ray astronomical observations further confirmed the extensive and universal physical connection between plasma object radiation and magnetic plasma activities.

3.2 X-ray Observations of Cosmic Plasma Objects

The X-ray band of the electromagnetic radiation spectrum also covers four orders of magnitude in wavelength from 100–0.01 Å, which can be further subdivided into soft X-rays (100–1 Å) and hard X-rays (1–0.01 Å). However, due to atmospheric absorption, X-ray astronomical observations must be conducted above the atmosphere. Early solar X-ray observations were mainly carried out by the U.S. Naval Research Laboratory after World War II using high-altitude rockets, with soft X-ray radiation from the Sun first detected in 1948. In the following 10 years, although rocket observation stability and pointing technology improved significantly, the effective observation time was too short (generally only 5 to 15 minutes). It was not until 1958 that hard X-ray radiation related to solar flares was first observed using high-altitude balloons, thus opening the prelude to solar high-energy radiation research [**?**]. Obviously, to study high-energy radiation related to transient phenomena like solar flares, long-term astronomical observation platforms are needed.

On October 4, 1957, the Soviet Union successfully launched humanity’ s first artificial Earth satellite, opening a new era of space science and providing a solid and reliable observation platform for space astronomy, especially X-ray astronomy. For example, after the U.S. “Orbiting Solar Observatory” series of satellites began launching in 1962, a large number of solar hard X-ray flare burst events were observed. The soft X-ray imaging telescope installed on “Skylab,” launched in 1973, with high resolution (angular spatial resolution reaching 5”), clearly revealed the rich and complex structures of magnetized plasma in the solar corona: “X-ray coronal loops” related to active region closed magnetic field structures, “X-ray bright points” associated with quiet region dipole magnetic fields, X-ray faint linear “filaments,” and large-area “coronal holes” with almost no X-rays [**?**]. With continuously improving resolution, it was further discovered that these complex coronal structures are actually composed of finer “filamentary” structures. Their formation and evolution are obviously closely related to the dynamical interaction between magnetic fields and plasma in the corona and constitute the most important observational data for studying the structural state and eruptive activity phenomena of the solar atmosphere.

For more than a decade after the first detection of solar X-rays, the Sun remained the only observed cosmic X-ray source, leading people to believe that there might be no strong X-ray radiation sources outside the solar system. It was not until June 1962 that Giacconi et al. from the American Society of Engineers unexpectedly discovered an X-ray source from a sky region not far from the Galactic center using a set of Geiger counters with specially enlarged area mounted on an Aerobee rocket [**?**]. This discovery immediately attracted the interest of Bowyer et al. at the U.S. Naval Research Laboratory, who had considerable experience in solar X-ray observations [**?**, **?**]. They built an X-ray counter ten times more sensitive than Giacconi' s group and limited the instrument' s field of view to 10° to improve positioning accuracy. As a result, they detected an extremely strong X-ray source in Scorpius (Scorpius X-1) and another slightly weaker X-ray source (about 1/8 the intensity of Scorpius X-1) in the Crab Nebula, about 20° from the Galactic center. Although this discovery opened the study of extrasolar X-ray astronomy, progress was very slow in the first 8 years due to the short duration of rocket observations. It was not until December 12, 1970, with the launch of the first dedicated X-ray astronomical satellite "Uhuru" by the United States, that a new era of vigorous development in X-ray astronomy truly began. Among the more than 300 X-ray sources detected by the Uhuru X-ray astronomical satellite, most were identified as close binary systems and supernova remnants within the Milky Way, as well as active galaxies and galaxy clusters beyond the Milky Way [**?**]. Uhuru' s most important discovery was identifying many strong X-ray sources in the Milky Way as close binary systems with mass exchange—systems composed of a compact star (white dwarf, neutron star, or perhaps black hole) and a normal star. The compact star continuously accretes matter from its normal companion through gravity, forming an "accretion disk" around itself. Matter in the accretion disk loses angular momentum through "mutual friction," thus continuously "falling toward the center" and releasing "gravitational energy." The released gravitational energy heats the accretion disk to millions or even billions of degrees, ultimately producing intense X-ray radiation three to four orders of magnitude higher than the Sun' s total radiation. This compact object accretion disk model was later widely applied to theoretical research on high-luminosity violent activity phenomena such as active galactic nuclei, becoming a typical template for constructing their central "driving engine," because the energy release efficiency of gravitational accretion processes for compact objects like neutron stars and black holes is more than ten or even dozens of times higher than thermonuclear fusion reactions inside stars. Another important discovery by Uhuru satellite was that intergalactic space within galaxy clusters is filled with tenuous hot gas at temperatures as high as 10^6–10^9 K. The origin and heating mechanism of this hot gas and its role in galaxy cluster dynamical evolution remain unexplained mysteries to this day [**?**].

The discoveries by Uhuru satellite greatly inspired confidence in X-ray astronomy research worldwide. The United States, the Soviet Union, Japan, and Europe successively launched a series of X-ray astronomical satellites. For example, the U.S. "Einstein Observatory" X-ray astronomical satellite launched in November 1978 and later the 1990s-launched European-American joint "Röntgen Satellite (ROSAT),"U.S. "Chandra X-ray Observatory,"and European "X-ray Multi-Mirror Mission"with higher detection precision all greatly enriched the distribution picture of high-temperature plasma in the universe. For instance, the Einstein Observatory not only improved instrument sensitivity by 1000 times but also achieved the first high-resolution imaging observations (spatial angular resolution of 2”) of extrasolar X-ray sources. Observations from these X-ray satellites revealed that all types of stars have X-ray emissions with luminosities ranging from 10^4 to 10^{-4} times the solar luminosity, implying that almost all stars have “stellar coronae” composed of high-temperature plasma similar to the solar corona and eruptive activity phenomena similar to solar flares [**?**, **?**, **?**, **?**, **?**]. [Figure 1: see original paper] shows the Hertzsprung-Russell diagram of about 2000 stars with X-ray coronae, where the size of the circles indicates the X-ray intensity of the stellar corona (as shown in the lower left corner, units erg/s; for comparison, the quiet solar corona X-ray luminosity is about 10^{26} erg/s), and different colors mark different statistical sources [**?**]. It is not difficult to see from [Figure 1: see original paper] that stellar coronae and their luminosities are quite widely distributed on the stellar H-R diagram, covering almost all types of stars at different evolutionary stages, and the luminosity variation spans several orders of magnitude. The heating mechanism of these coronae, including the solar corona, has long been an unresolved fundamental problem in astrophysics.

With the aid of high-resolution observations from these X-ray satellites, not only were stellar coronae in extragalactic galaxies discovered as individual X-ray sources for the first time, but also the distribution of intergalactic hot gas on galaxy cluster scales was further discovered, and the “fine structure” of the distribution of this hot gas within galaxy clusters was resolved. This implies that there may be coronal magnetic plasma atmospheric activity phenomena similar to solar active regions in galaxy clusters, just on much larger scales. The left panel of [Figure 2: see original paper] shows the soft X-ray distribution (dark red) of the Coma galaxy cluster composed of thousands of galaxies obtained by the Röntgen satellite, where the gray bright spots are the visible-band galaxy imaging from the Palomar survey telescope [**?**]. This X-ray image clearly shows the overall independence and structural integrity of the galaxy cluster as the largest-scale “celestial body” in the universe, whose main body is high-temperature hot plasma with a scale up to hundreds of millions of light-years. As seen in the left panel of [Figure 2: see original paper], there are two huge giant elliptical galaxies in the central region, with a significantly enhanced X-ray brightness compact core region centered on them, covering a scale of millions of light-years. The right panel of [Figure 2: see original paper] shows the turbulent structure of the hot plasma pressure distribution in the core region, with the maximum turbulent scale reaching nearly 500,000 light-years [**?**].

In some galaxy clusters with active galactic nuclei at their centers, complex large-scale dynamical structures such as jets, cavities, and shocks similar to those shown in solar active regions are also observed. For example, panels (a) and (b) of [Figure 3: see original paper] respectively show the X-ray imaging of the central regions of the Virgo cluster and Perseus cluster obtained by the Chandra satellite [**?**]. From panel (a), the relativistic high-energy plasma jet ejected from the central giant elliptical galaxy M87 and multiple ring-like structures can be clearly seen, while panel (b) displays the complex magnetic plasma dynamical structure of cavities, rings, and wavefronts interwoven in the Perseus cluster.

Not only are relatively dense high-temperature plasmas distributed near galaxy cluster centers (also known as intracluster hot media), which are the largest-scale X-ray radiation sources in the universe, but there may also be large amounts of tenuous high-temperature plasma media in the vast cosmic space between galaxy clusters far from cluster centers. In recent years, through observational studies of the so-called Sunyaev-Zeldovich effect caused by inverse Compton scattering between high-temperature thermal electrons and cosmic microwave background radiation photons, it has been confirmed that the vast space between galaxy clusters is also filled with tenuous high-temperature plasma [?, ?, ?, ?]. In fact, comprehensive astronomical observations at various electromagnetic bands show that 90% of observable cosmic matter is diffusely distributed throughout the vast cosmic space in the form of galactic halos, intergalactic or intercluster hot media. In contrast, the aggregated celestial matter such as stars and galaxies observed in traditional optical astronomy accounts for only 10% of the total observable cosmic matter [?, ?, ?]. These diffuse thermal media that dominate observable cosmic matter are generally high-temperature plasmas at temperatures of 10^6–10^9 K, diffused throughout the vast intergalactic space of the universe. The origin and heating mechanism of these tenuous high-temperature plasmas during cosmic evolution accompanied by expansion and cooling have always been unsolved mysteries [?, ?, ?, ?]. They must play key roles in the dynamical processes of large-scale structure formation and energy conversion in celestial eruptive activity phenomena, representing important issues that future cosmic evolution and astrophysics must consider and fundamental topics that plasma astrophysics needs to study.

3.3 Correlation Between Cosmic Plasma Object Radiation and Magnetic Fields

According to relevant theories of cosmic plasma object radio radiation mechanisms, celestial radio radiation is mainly magnetic bremsstrahlung from nonthermal high-energy electrons in magnetic fields (such as synchrotron radiation from radio galaxies or curvature radiation from radio pulsars) [?, ?, ?]. Their radiation energy loss rate (i.e., radio radiation luminosity) must be closely related to celestial magnetic fields. On the other hand, X-ray radiation produced mainly by Coulomb bremsstrahlung from collisions between thermal electrons and ions in high-temperature plasma objects has a luminosity that depends only on the temperature and density of the plasma objects, with no direct relationship to magnetic fields. However, statistical analysis of numerous observations shows that there is a consistently good correlation between radio radiation luminosity and X-ray luminosity of plasma objects over a very wide range of scales. The left panel of [Figure 4: see original paper] shows that the X-ray and radio band radiation luminosities of solar flares and some stellar coronae exhibit good consistent correlation across nearly 10 orders of magnitude [?], while the right panel further shows that the highly consistent correlation between X-ray and radio radiation luminosities of strong radiation sources from X-ray binaries to active galactic nuclei spans an even broader scale range of 15 orders of magnitude [?]. These radio and X-ray radiations not only have completely different direct emission sources (non-thermal high-energy electrons and high-temperature thermal electrons, respectively) but also completely unrelated radiation mechanisms (magnetic bremsstrahlung and Coulomb bremsstrahlung, respectively). The widely consistent high correlation between their radiation luminosities implies that there must be some highly correlated or even common energy supply mechanism behind these two radiation processes that can very effectively accelerate non-thermal high-energy electrons and heat high-temperature plasma. Among the energy supply mechanisms that can simultaneously satisfy these conditions, magnetic fields and their magnetic energy are undoubtedly the most suitable candidates to play important roles. Observational statistical analysis of plasma object X-ray luminosity and magnetic flux further confirms this.

The left panel of [Figure 5: see original paper] shows the power-law correlation between X-ray intensity of solar coronal loops and the corresponding coronal loop magnetic field strength [?], where different colors correspond to six groups of solar Carrington rotations during different declining phases of solar magnetic activity, covering a large variation range of coronal loop magnetic field strength. The power-law correlation shown in the left panel of [Figure 5: see original paper] implies that the heating mechanism of solar coronal loops has close intrinsic physical connections with coronal magnetic fields, and the heating efficiency shows a positive correlation trend with magnetic field strength. The right panel of [Figure 5: see original paper] further extends this power-law correlation between X-ray luminosity and corresponding magnetic flux from the Sun to other active celestial bodies [?], maintaining good power-law positive correlation characteristics across scale variations spanning more than ten orders of magnitude, further proving that the intrinsic physical connection between magnetic fields and plasma heating mechanisms universally exists in the heating phenomena of high-temperature plasma in the universe.

Based on the modern astronomical observational fact that magnetic fields and high-temperature plasma universally exist at different scales of cosmic object structures, we propose that kinetic Alfvén waves can serve as a universal heating mechanism for cosmic high-temperature plasma objects [?]. In fact, a universal characteristic of cosmic plasma objects is their relatively high free energy. Near gravitational centers, this free energy provides the driving energy source for celestial eruptive activity phenomena, and accompanying energy release may also cause some local and transient heating phenomena. However, for maintaining high-temperature states, especially for intergalactic high-temperature plasmas far from gravitational centers, a heating mechanism that can continuously and stably occur universally is needed. Modern astronomical observations show that magnetic fields of various scales universally exist in the vast cosmic space. When magnetic fields are present, any oscillation of magnetic field lines will inevitably excite Alfvén wave disturbances, thus inevitably forming universally existing Alfvén wave turbulence in the extensive cosmic space. According to the Goldreich-Sridhar theory of Alfvén wave turbulence in interstellar media [**?**, **?**, **?**], the nonlinear wave-wave coupling of Alfvén wave turbulence will lead to the transfer of turbulent wave energy to small scales until approaching the micro-dynamical scales of plasma particles, evolving into kinetic Alfvén wave turbulence. Through wave-particle interactions between kinetic Alfvén waves and particles, effective energy and momentum exchange between waves and particles is achieved, thereby heating or accelerating plasma particles. This universal physical picture, when applied to structured solar coronal heating phenomena, can well explain the magnetic correlation and structural non-uniformity characteristics of coronal heating [**?**, **?**, **?**, **?**]. Based on the universal and consistent correlation between X-ray luminosity and magnetic fields of various cosmic plasma objects at different scales, we have reason to believe that the solar coronal heating mechanism based on kinetic Alfvén waves can also become a universally effective heating mechanism for other cosmic high-temperature plasma objects [**?**].

4 Eruptive Activity Phenomena of Cosmic Plasma Objects and Their Energy Conversion Mechanisms

The expansion of modern astronomical observation technology to all-waveband astronomy has not only given rise to new astronomical branches such as radio astronomy and X-ray astronomy, revealing an unprecedented picture of cosmic matter distribution and structure, but also greatly expanded the research horizons of astrophysics and caused a major shift in research direction. In particular, high-energy eruptive activity phenomena of celestial bodies (such as Earth’ s aurora and magnetic storms, solar flare eruptions and coronal mass ejections, supernova explosions, extragalactic radio jets, cosmic gamma-ray bursts, and fast radio bursts) and their dynamical driving mechanisms have become the mainstream direction of contemporary astrophysics research and important topics in plasma astrophysics. Among various celestial eruptive activity phenomena and their driving mechanisms, one of the fundamental issues involved is the energy conversion process of energy storage, transport, and release during eruptions.

In modern human social life, the most familiar energy transmission and conversion mechanism is the generator and its power transmission system. In fact, similar “generators and power transmission systems”often play important roles in celestial eruptive activity phenomena. For example, the driving system behind Earth’ s magnetic storms and aurora is the direct result of the electrodynamical evolution of the global current system formed by solar wind-magnetosphere-ionosphere coupling. The global current system is mainly interconnected by several current loops: (1) magnetopause current along the magnetopause interface (also called Chapman-Ferraro current), (2) magnetotail current surrounding the magnetotail column, (3) neutral sheet current flowing along the magnetotail neutral sheet, (4) ring current in the magnetospheric radiation belt around Earth,

(5) field-aligned current along Earth' s polar magnetic field lines (also called Birkeland current), and (6) ionospheric current [?, ?]. Among them, the magnetopause current and magnetotail current are mainly surface currents flowing along the magnetospheric boundary layer driven by solar wind-magnetosphere interaction, and are also the main driving "generators" of the global current system. The neutral sheet current is mainly formed by the reversal of north and south magnetic field lines in the magnetotail along the magnetic neutral plane. The ring current is mainly formed by the drift motion of high-energy particles in the magnetospheric radiation belt across Earth' s dipole magnetic field lines and is the direct driving current causing magnetic storms, while aurora (or substorms) are mainly driven by polar field-aligned currents, generally related to the injection of magnetotail and neutral sheet current activities along magnetic field lines into Earth' s polar regions. As for ionospheric current, it consists of Pedersen current and Hall current, formed by the relative drift of ionospheric electrons and ions parallel and perpendicular to the electric field under the dual action of electric fields and collisions, respectively, and also plays a role in circuit linking between polar field-aligned currents. During relatively quiet solar wind periods, it is the magnetic field generated by the global current system that causes Earth' s magnetic field to deviate from a dipole field, forming severe asymmetry in magnetopause and magnetotail structures. When solar wind disturbances are violent, energy and momentum input through the solar wind-magnetosphere interaction boundary layer will drive strong disturbances in the global current system, causing rapid enhancement of magnetospheric ring current and polar field-aligned current, and ultimately releasing the "overloaded" energy stored in the global current system by triggering magnetic storms and magnetospheric substorms [?].

Space satellite in-situ detection has provided a solid experimental foundation for the theory of Earth' s magnetosphere global current system [?]. Based on the high similarity between the solar corona-chromosphere-photosphere atmospheric structure and the Earth' s magnetosphere-ionosphere-upper atmosphere structure in both microscopic plasma magnetization characteristics and macro-electrodynamical coupling characteristics [?, ?, ?, ?, ?], we have reason to believe that a solar magnetic plasma atmospheric current system similar to the magnetosphere global current system exists in the solar atmosphere. Their electrodynamical evolution and explosive discharge processes are the physical driving mechanisms for solar flares and coronal mass ejections and other eruptive activity phenomena [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. Unlike the driving generator of Earth' s magnetosphere current system, which comes from the external solar wind-magnetosphere interaction boundary layer, the driving generator of the solar atmospheric magnetic plasma current system is more likely to mainly originate from the solar internal convection zone and the turbulence it drives in the photosphere.

As Alfvén pointed out in his book "Cosmic Plasma" [?], the above Earth's magnetosphere current system and solar atmospheric magnetic plasma current system may be only part of a heliospheric current system with larger spatial scales and higher energy capacity. The entire heliospheric current system links the Sun' s internal thermonuclear fusion reactor, through the solar atmosphere and solar wind, to the heliospheric boundary layer, connecting with the interstellar medium and magnetic fields of the Milky Way. The solar atmospheric current system, heliospheric current sheet, interplanetary coronal mass ejection current-carrying loops, heliospheric boundary layer currents, and magnetospheric current systems of Earth and other planets will all be components of the entire heliospheric current system. Similar to the Sun' s heliospheric current system, other stars may also have similar "stellar current systems," where the internal thermonuclear fusion reactor of the star and the interaction boundary layer between the external galactic environment medium and stellar wind may provide the main driving generator for the stellar current system.

Alfvén even extended this type of heliospheric or more general stellar current system to extragalactic radio galaxies, forming galactic current systems with intergalactic scales. The Cygnus A radio source is the earliest discovered and strongest radio galaxy observed, with radio radiation power as high as $\sim 10^{44}$ erg/s, $\sim 10^{6}$ times the radio radiation power of the Milky Way. The left panel of [Figure 6: see original paper] shows the huge radio jets and radio lobe structures of Cygnus A, with a faint elliptical galaxy at its center, while the right panel shows a schematic diagram of the galactic current system connecting the central galactic nucleus (galaxy-scale rotating black hole) and the radio lobes [?]. In this galactic current system, the electric potential distribution along the galactic axis can accelerate high-energy charged particles and form the main current channel along the galactic axis. The relativistic high-energy electrons are both the main current carriers of the galactic current system and the direct radiation source producing radio jets and radio lobes [?], while the strong gravitational field of the central supermassive rotating black hole or the interaction between surrounding intergalactic high-temperature plasma and galactic or cosmic magnetic fields may provide the main driving generator for the galactic current system.

Combined with observational displays of relativistic high-energy electron beams and high-temperature plasma spatial distributions from radio and X-ray radiation of active galaxies, there seems to be evidence confirming the possible existence of galactic circuit structures corresponding to such super-large-scale galactic current systems. [Figure 7: see original paper] shows the distribution of radio radiation (red, observed by VLA) and X-ray radiation (blue, based on Chandra satellite observations) of galaxy cluster MS 0735.6+7421. For comparison, the distribution of galaxies within the cluster (white, captured by the Hubble Space Telescope) is also superimposed [?]. As shown, radio and X-ray radiation have significantly different spatial distribution characteristics, implying that radio jets representing relativistic high-energy electron beams extend from the central galaxy along the galactic axis to both sides, while X-ray radiation representing high-temperature plasma is distributed in an axisymmetric halo surrounding the radio jets. This shows good analogy with the spatial distribution characteristics of the galactic current system shown in [Figure 6: see original paper]. On the other hand, the clearly separated spatial distribution characteristics of non-thermal high-energy electrons and high-temperature plasma with different plasma components imply the existence of large-scale galactic magnetic fields that must play important roles in the electrodynamical processes of galactic current system formation and evolution.

Modern astronomical observations and cosmic evolution theories both show that since entering the reionized plasma universe, the distribution of observable matter has formed local gravitational centers at different scales from planets and stars to galaxies and galaxy clusters under the action of Jeans gravitational instability, evolving toward increasingly highly structured directions. During the collapse of surrounding matter toward local gravitational centers, gravitational potential energy is converted into kinetic energy (or thermal energy), plasma turbulent wave energy, and electromagnetic energy of current systems. In particular, in non-uniform environments caused by local gravitational centers, reionized plasma will produce macroscopic separation motions during gravitational collapse due to significant differences in charge-to-mass ratios between ion and electron components, leading to the formation of local charge and current distributions. Due to the collective interaction characteristics of plasma, these local charge and current distributions will eventually form complex but relatively steady-state current systems through self-organization, storing large amounts of energy in the form of macroscopic electromagnetic energy in "electric double layers" and "inductance" regions of the current systems. It is the electromagnetic energy stored in these local current systems of plasma objects that provides the main driving energy source for celestial eruptive activity phenomena. When they accumulate to a certain threshold and exceed the carrying capacity of the quasi-steady-state current system, they will trigger instability in the current loop, leading to explosive release of stored electromagnetic energy. This explosively released electromagnetic energy mainly excites strong plasma turbulent waves in surrounding plasma objects through plasma instability excitation processes, causing originally quasi-steady-state background plasma to rapidly enter a strong turbulent state. Through plasma wave-particle interaction processes, non-thermal high-energy particles are accelerated and high-temperature plasma is heated, becoming the main direct radiation sources for radio and X-ray radiation of plasma objects, respectively.

In this physical picture where gravitational energy is converted through plasma object current systems, stored as macroscopic electromagnetic energy in current systems, and then explosively released through "overload" instability, ultimately leading to cosmic celestial eruptive activity phenomena, cosmic background magnetic fields must play a crucial and important role, even dominating the formation process and structural distribution of local quasi-steady-state current systems. As modern astronomical observations reveal, high-temperature plasma distributed throughout cosmic space is the main component of observable cosmic matter. Modern astronomical observations also show that the existence and structure of magnetic fields permeate all celestial scales from planets and stars to galaxies and galaxy clusters [**?**]. The origin of these magnetic fields has been widely debated and remains an unsolved mystery. The main viewpoints can be divided into two categories: one is the so-called cosmological origin theory, which suggests that so-called “seed” magnetic fields may have been produced in the very early universe and survived to this day like cosmic background radiation, being “compressed” into local gravitational centers by plasma flows during cosmic evolution; the other is the astrophysical origin theory, which suggests spontaneous generation through dynamo mechanisms accompanying the formation of plasma object structures [**?**, **?**]. However, regardless of their origin, as Alfvén pointed out long ago: magnetic fields exist everywhere in the universe, and the interaction between plasma and magnetic fields is of great significance for space and astrophysics [**?**].

Undoubtedly, traditional astronomy has always been a modern science based on astronomical observations. It is precisely because of the two major breakthroughs in astronomical observation technology—from visible light windows to all-waveband observations and from ground-based to above-atmosphere space observations—that a completely new cosmic picture has been presented to humanity. Among them, the dominant component occupying 90% of observable cosmic matter is not stars and galaxies scattered in the vast cosmic space shining with starlight, but high-temperature plasma that, like cosmic background radiation, diffuses and fills the entire cosmic space. At the same time, under the combined action of long-range electromagnetic forces and gravity, their distribution in cosmic space is neither as uniform as background radiation nor as concentrated as stars and galaxies. Moreover, particularly due to the collective interaction characteristics caused by long-range electromagnetic coupling between particles in these relatively diffuse cosmic plasma objects, they exhibit far more complex micro-dynamical processes and macro-dynamical evolution than neutral matter. However, most of these complex dynamical characteristics cannot be directly reflected in their electromagnetic radiation, making it difficult for us to obtain information about the dynamical properties of these plasma objects from astronomical observations. For example, complex wave states in plasma objects and their wave-particle interaction processes, large-scale magnetized plasma structures such as current-carrying magnetic flux tubes and collisionless shocks, and the structure and evolution of quasi-steady-state current systems are difficult to obtain reasonable physical speculation and diagnosis through astronomical observations of radiated electromagnetic waves because they are not directly related to the generation of electromagnetic radiation by plasma objects and are “invisible”phenomena in astronomical observations. However, the collective dynamical behavior of plasma objects generally follows the so-called “scaling law,” meaning that plasma objects with the same dimensionless scaling parameters also have similar collective dynamical behavior. This allows results from laboratory plasma measurements and space plasma in-situ detection to be appropriately extrapolated to other distant plasma object environments, providing another possible research approach for modern plasma astrophysics besides astronomical observations.

5 Natural Laboratory for Plasma Astrophysics: In-Situ Satellite Detection Studies of Space Plasmas

Although people realized more than 100 years ago, when the Saha equation was proposed, that more than 99% of observable cosmic matter might be plasma in the fourth state, the true understanding of the specific structure and existence mode of these cosmic plasmas only came after humanity entered the space age. Since the launch of the first artificial satellite into space above Earth' s atmosphere in 1957, in-situ satellite detection of space plasmas has unveiled a material world completely different from the neutral gas environment on the ground. It has not only confirmed previous speculations about Earth' s atmospheric space environment and solar-terrestrial relations but also discovered a large number of unexpectedly complex magnetized structures and physical states of plasma objects, which are far more complex than previously imagined.

Before human space exploration activities began, it was already recognized that besides sunlight, there must be some other direct connection between the Sun and Earth. As early as the mid-19th century, based on long-term accumulated observations of sunspots and geomagnetic disturbances (i.e., magnetic storms), it was discovered that "geomagnetic disturbance intensity is related to the sunspot cycle." In particular, on September 1, 1859, British astronomer Carrington suddenly observed a large solar flare while drawing a sunspot group [**?**]. About 16 hours later, a geomagnetic observatory in London recorded obvious geomagnetic disturbances, and the strongest magnetic storm in recorded history occurred, accompanied by strong aurora, indicating that Earth' s magnetic storms and aurora are indeed related to solar flare and other eruptive activity phenomena. Around the early 20th century, Norwegian physicist Birkeland applied Thomson's discovered electron theory to his aurora theory, further pointing out that what caused magnetic storms and aurora were precisely electron beams from solar flares [**?**]. In the 1930s, Chapman and Ferraro systematically developed this theoretical model of plasma flows from the Sun interacting with Earth' s magnetic field, establishing the early concept of Earth' s magnetosphere structure—the "magnetic cavity" —and further explaining the physical mechanism of magnetic storm formation [**?**, **?**]. When humanity entered the space age in 1957, the above hypotheses and theories about the existence of solar wind plasma flows and their interaction with Earth' s magnetic field causing magnetic field dragging and effects on geomagnetic activity and aurora were soon confirmed by in-situ space satellite detection. At the same time, it was also discovered that both the solar wind and Earth' s magnetosphere have far more complex structural states and dynamical processes than originally assumed.

First, Professor Van Allen from the University of Iowa used cosmic ray detectors on the first two space exploration satellites launched by the United States after the Soviet Union, "Explorer-1 and -2" in 1958, to discover high-energy particle radiation belts in the magnetosphere (now called the "Van Allen radiation belts"), filled with high-energy charged particles with energies ranging from 1 keV to 100 MeV captured by Earth' s dipole magnetic field. Their energies are far higher than the thermal energy of solar wind particles, and the corresponding energization mechanism remains an open question to this day [?]. The drift motion of these radiation belt high-energy charged particles captured by Earth' s magnetosphere around Earth forms the ring current, constituting part of the magnetosphere global current system. However, the sudden enhancement of ring current caused by violent solar wind disturbances is the direct cause of magnetic storms. On the other hand, aurora—the only solar-terrestrial connection phenomenon visible to the naked eye besides sunlight—is not as simple as originally imagined, being directly caused by high-energy particles from the Sun propagating downward along Earth' s magnetic field. Comprehensive satellite observations crossing polar regions show that the high-energy electrons directly causing aurora mainly come from within the magnetosphere at altitudes of about 5,000 km to 10,000 km above Earth' s polar regions, called the "auroral acceleration region," with energy mainly distributed in the 1-10 keV range [?]. The acceleration mechanism is generally believed to be related to the existence of field-aligned electric fields and their field-aligned potential drops, which may originate from strong disturbances in magnetotail neutral sheet current caused by solar wind disturbances and even trigger magnetic reconnection, leading to sharp increases in polar field-aligned currents (also called "Birkeland currents" or "auroral currents"), but the specific physical mechanisms remain controversial [?, ?, ?, ?].

Additionally, when Explorer-10 and -12, Mariner-2, and Helios-1 and -2 launched in the 1960s and 1970s successively crossed the magnetopause and entered outer interplanetary space, it was discovered that interplanetary space indeed contains continuous supersonic plasma flows from the Sun with speeds up to several hundred kilometers per second. In-situ detection found average densities between 1-10 cm^{-3}, temperatures around 10^5 K, magnetic fields between 10^{-5}-10^{-4} Gs, and main components of electrons and protons with about 4% alpha particles. In particular, the supersonic solar wind plasma flow not only universally contains large amounts of various mode plasma waves and strong turbulence but also frequently accompanies various large-scale magnetized plasma structures [?]. For example, when Explorer-12 crossed the magnetopause into the solar wind, it discovered a sudden change in the solar wind before reaching the magnetopause. Later, many satellites entering interplanetary space clearly indicated the existence of this transition layer near the magnetopause. This transition layer of the solar wind is actually a shock wave produced when the supersonic solar wind plasma flow encounters the obstacle of Earth' s magnetosphere. However, the thickness of the shock layer is only on the order of ion dynamical scales, far smaller than the mean collision free path of solar wind particles. The discovery of this "collisionless shock" greatly surprised space physicists at the time, because in ordinary gases, shock formation is a stable structure formed when nonlinear steepening effects caused by supersonic flows balance with particle collision dissipation effects, with typical thickness on the order of particle mean collision free paths. However, further detection discovered that such "ultra-thin" collisionless shock structures universally exist in interplanetary solar wind plasma, some as thin as the order of electron inertial lengths. Although the formation mechanism of such collisionless shocks remains an open problem to be solved, their unique magnetic plasma structure enables them to provide a very effective particle acceleration and heating mechanism that has been widely applied in high-energy astrophysical phenomena [**?**].

Another important discovery concerns the observation of interplanetary magnetic clouds. In 1981, Burlaga et al. discovered a class of "magnetic loop" structures with spiral magnetic field lines in interplanetary solar wind through comprehensive analysis combining multi-satellite observation data from Voyagers, Imp 8, and Helios. These structures are called "interplanetary magnetic clouds" and have three main observational characteristics: (1) significantly enhanced magnetic field strength, (2) continuously smooth rotation of magnetic field direction, and (3) significantly decreased plasma dynamic pressure-to-magnetic pressure ratio [**?**]. Such events were later confirmed to be current-carrying magnetic flux tubes directly ejected from the solar atmosphere into interplanetary space during solar eruptive activity, carrying total energy that exhibits a negative power-law energy spectrum similar to solar flares within their typical scale distribution range of 0.01–0.25 AU [**?**, **?**]. This discovery reveals that current-carrying magnetic flux tubes, or what Alfvén called "plasma cables" [**?**], as components of plasma object current systems, may universally exist in various cosmic plasma objects and constitute important links in the electrodynamical evolution of plasma object current systems. Satellite in-situ detection studies of their propagation processes in interplanetary space have irreplaceable experimental value and exemplary significance for our better understanding of the structural states and dynamical evolution of other plasma object current systems.

As Voyager 1 and 2 satellites successively crossed the solar wind termination shock and heliopause [**?**], the range of human satellite in-situ detection has crossed the heliospheric boundary layer into interstellar space, discovering complex boundary layer structures similar to those formed by Earth' s magnetosphere-solar wind interaction, such as the magnetopause, magnetosheath, and bow shock. In the interaction region between heliospheric solar wind and interstellar medium, there also exist heliospheric boundary layer structures composed of the solar wind termination shock, heliosheath, and heliopause [**?**]. Undoubtedly, a series of new discoveries from satellite in-situ detection, including ionosphere and magnetosphere structures, Van Allen high-energy particle radiation belts and their plasma waves, magnetopause, magnetosheath and bow shock, supersonic solar wind plasma flow and its turbulent waves, interplanetary collisionless shocks, corotating interaction regions, heliospheric current sheet and interplanetary magnetic cloud current-carrying magnetic flux tubes, as well as Earth' s magnetosphere global current system and heliospheric current system, have completely updated our understanding of the near-Earth space environment and heliospheric plasma structure.

According to Alfvén' s suggestion [**?**], extrapolating this to other distant cosmic plasma object systems, it is not difficult to imagine that around local gravitational centers such as planets, stars, galaxies, and galaxy clusters and their surrounding plasma media boundaries, there may universally exist surface boundary layer structures that wrap them. If we follow Alfvén [?] and call these plasma object systems wrapped by boundary layers "cells," then these boundary layers that both isolate the surrounding environment and exchange energy with it are "cell walls," the plasma current systems mainly responsible for energy storage and transmission are the "blood circulation" flowing within these cells, the plasma and its turbulent waves filling local interplanetary, interstellar, intergalactic, and intercluster cosmic spaces are the "muscles" of the corresponding cells, and the local gravitational centers that can convert gravitational energy into electromagnetic energy are the "hearts" of these cells. However, for those plasma object systems in distant cosmic space, their magnetic plasma "cell" structures are almost invisible in traditional astronomical observations and can only be probed for their structural states and dynamical behavior through in-situ measurements. Currently, the only "cell" sample that humans can conduct satellite in-situ detection on is the heliosphere and the magnetosphere systems of planets within it. Therefore, their "demonstration" significance for understanding the complex structures and dynamical behavior of other distant cosmic plasma object systems is obvious.

For example, without space satellite in-situ detection research, our physical understanding of the structural states and dynamical coupling relationships of space magnetic plasma structures such as Earth' s ionosphere, radiation belts, magnetosphere, magnetopause, collisionless shocks, solar wind turbulence, plasma cables, heliospheric boundary layer, and global current systems might still be groping, debating, and wandering in the "dark," or even seriously misled. Research on solar flare magnetic reconnection driving mechanisms and solar radio burst coherent radiation mechanisms are two typical examples. In solar flare magnetic reconnection driving mechanism research, a common misconception is that flares occur at the magnetic reconnection region. However, satellite space detection research related to Earth' s aurora phenomena shows that the magnetic reconnection region driving aurora is actually in Earth' s magnetotail neutral current sheet, while the acceleration of auroral high-energy electrons occurs in the polar magnetosphere, and the ionosphere bottom where aurora occurs is only the final energy dissipation region. In most key regions of the auroral circuit energy transmission chain, since they do not produce strong electromagnetic wave radiation, they are almost completely invisible "dark regions" in traditional "astronomical observations," which Alfvén called "invisible energy transmission" [?]. As for the radiation mechanism of solar radio bursts, due to the lack of in-situ detection knowledge about the structural state of the radiation source region, there has been long-standing controversy between plasma radiation and electron cyclotron maser radiation mechanisms. In contrast, for Earth' s auroral kilometric radiation, because a large amount of satellite in-situ detection data has been accumulated about its radiation source region, its electron cyclotron maser radiation mechanism has been universally recognized without dispute.

Therefore, for modern plasma astrophysics research, due to the complexity of cosmic plasma object system "cell-like" structures and electrodynamical processes, especially the "invisibility" of their current systems and energy transmission processes, traditional astronomical observation methods relying solely on electromagnetic radiation from plasma objects are far from sufficient. We must fully utilize the "experimental research" results from the natural "plasma astrophysics laboratory" provided by in-situ satellite detection of Earth' s magnetosphere and heliosphere space plasma and appropriately extrapolate them to other cosmic plasma object environments. Such extrapolation requires us to reconstruct the structure and state of cosmic plasma objects based on the fundamental physical characteristics of plasma collective interactions, establish a completely new plasma cosmology, which will undoubtedly bring huge and far-reaching impacts to the development of modern astronomical research. As Professor Alfvén pointed out in the preface to the Chinese version of his monograph "Cosmic Plasma" [**?**]: "Three or four centuries ago, Galileo invented the telescope, which changed our understanding of the cosmic environment. Similarly, the Soviet Union' s first artificial satellite launched by Korolev and the cutting-edge measurement technology developed by Van Allen have brought similar huge changes to space physics research. As a result, extrapolation from laboratory measurements and magnetospheric measurements to astrophysics is causing a profound change in astrophysics comparable only to the Copernican-Galilean revolution."

6 Summary and Outlook: The Third Astronomical Revolution and Plasma Cosmology

Since humanity entered the space age, modern all-waveband astronomical observations free from atmospheric obstacles have presented us with a cosmic picture completely different from that recognized by traditional optical astronomy since Galileo pointed the telescope skyward. In this new cosmic picture, the main component constituting observable cosmic matter is not stars and galaxies scattered in the cosmic firmament, but interstellar, intergalactic, and intercluster hot media and high-energy particle beams diffused in the vast cosmic space. They are universally in a tenuous high-temperature plasma state, are the main observational research objects of modern radio astronomy and X-ray astronomy, but are "invisible" observable matter in the field of view of traditional optical astronomy. This has also brought major changes to astrophysics, making high-energy eruptive activity phenomena of various celestial bodies the mainstream direction of contemporary astrophysics research and deriving a new branch discipline—plasma astrophysics—with plasma objects and their activity phenomena as the main research objects.

Since the birth of plasma astrophysics in the 1960s, remarkable successes have been achieved in radio and X-ray astronomy. For example, it has greatly promoted the development of X-ray radiation transfer theory for high-temperature thermal electrons and non-thermal high-energy electrons and achieved wide application in the physical diagnosis of various thermal and non-thermal X-ray sources, greatly expanding human understanding of cosmic object structures and states [**?**]. In radio astronomy, research on theoretical models of spontaneous and induced radiation mechanisms of high-energy electron beams in plasma has also provided powerful diagnostic tools for astrophysical research on various cosmic radio sources from Earth' s auroral kilometric radiation, solar radio bursts to radio pulsars and radio galaxies [**?**, **?**]. At the same time, a large number of observational analyses and theoretical research works have been carried out on the microscopic physical mechanisms of heating cosmic high-temperature plasma and accelerating non-thermal high-energy electron beams, which have always been the main key research areas of plasma astrophysics [**?**]. However, observations of electromagnetic radiation from plasma objects mainly reflect physical information about their energy release processes, which are directly related to radiation mechanisms but have no direct connection with their heating and acceleration processes or the transmission and storage processes of heating and acceleration energy. As Alfvén pointed out [**?**], these are closely related to the "invisible energy transmission" processes in electromagnetic radiation observations. In fact, the "invisibility" of important physical processes in plasma object systems is also determined by the complex "collective" dynamical nature of cosmic matter in the plasma state. Their study requires new astronomical research methods beyond traditional astronomical observations of electromagnetic radiation from celestial bodies—the "experimental extrapolation" method based on in-situ satellite detection of space plasma.

Based on the so-called standard Big Bang cosmological model, from early hot universe quark-gluon plasma, baryon-lepton plasma, and proton-electron plasma to reionized plasma after recombination, the basic state of cosmic matter has always been plasma. Therefore, plasma astrophysics is not only the theoretical foundation for comprehensively and completely analyzing the structural states and eruptive activity mechanisms of reionized cosmic plasma objects but also an essential key to understanding the early hot universe and its expansion history. However, due to the collective interaction characteristics of electromagnetic coupling between microscopic particles in plasma objects, although each particle follows familiar classical equations of motion, the electromagnetic interaction coupling of numerous particles exhibits extremely complex and unpredictable collective behavior. The reason should be the complex strong nonlinear characteristics of electromagnetic coupling in multi-particle systems. As demonstrated by the fact that space plasma satellite in-situ detection has discovered a large number of cosmic structures and behaviors that traditional astronomical observation methods cannot find, existing theoretical reasoning and prediction often appear powerless for understanding the dynamical behavior of plasma objects, requiring more reliance on empirical knowledge accumulated from experimental measurements. Therefore, relying solely on astronomical observation methods is insufficient to solve most problems encountered in plasma astrophysics research. We must utilize experimental knowledge and empirical models established on the basis of space satellite in-situ measurements and extrapolate them to other cosmic plasma object systems to more accurately understand the role of collective interaction characteristics of plasma objects in various celestial structural states and eruptive activities.

As described in the previous section, with the development driven by Jeans gravitational instability, the basic distribution characteristic of cosmic reionized plasma object matter is the formation of a series of local gravitational centers at different scales, with "hearts" at local gravitational centers, "blood vessels" as plasma current systems, and "cell walls" as interaction boundary layers—organic "cell" structures. Under the combined action of central gravitational fields and electromagnetic forces, surrounding magnetic plasma forms a series of local current systems through self-organization processes of collective interactions. An important function of these local current systems is to convert gravitational energy (or other forms of energy derived from gravitational energy) into electromagnetic energy in their "active plasma regions (generator regions)" and transport it through current systems to "passive plasma regions (dissipation regions)" [**?**]. When the current or energy stored in the current system reaches a certain instability threshold, it will trigger instability and lead to large-scale sudden release of stored electromagnetic energy. This released energy initially mainly excites strong turbulent plasma waves in surrounding plasma objects, which is then converted into plasma particle energy through wave-particle interactions, existing in the form of non-thermal high-energy particle beams or local high-temperature hot plasma, accompanied by strong bursts of radiated electromagnetic waves.

In the formation process of these cosmic plasma object organic "cell" structures, there are two key core factors: one is the competition and cooperation between gravity and electromagnetic forces; the other is the essential characteristic of plasma collective interactions. The coupling of these two factors leads to a series of complex energy transmission and conversion processes. However, in the series of energy transmission and conversion processes from initial gravitational energy to final electromagnetic radiation wave energy, only information about the final radiated electromagnetic energy can be observed through various astronomical telescopes, while the series of magnetic plasma structures and collective dynamical processes are undetectable by astronomical observation methods. Therefore, besides traditional astronomical observation methods, we must rely on other research methods to obtain physical information about the magnetic plasma structures and current systems of plasma objects. The planetary magnetosphere and heliosphere plasma and their current systems are undoubtedly one and the only cosmic plasma object system that can be detected by satellite in-situ detection. Therefore, they are also important natural laboratories for plasma astrophysics research. However, to date, most astronomers seem not to have fully realized the importance of this natural laboratory for modern astronomy and astrophysics research.

Alfvén even believed that the extrapolation of space plasma measurement results to other cosmic plasma objects will bring the third revolution in astronomy [?]. The first revolution in astronomy was the revolutionary shift from geocentrism to heliocentrism brought about by the combination of Galileo' s telescope observations more than 400 years ago and Newton' s gravitational theory, which established the static, uniform, and stable cosmology based on Newton' s universal gravitation theory. The second revolution was the major shift from a static and stable cosmology to a dynamic and evolutionary cosmology brought about by the combination of Hubble expansion observations of celestial redshift phenomena in the early 20th century with relativity and quantum theory. Its core was the establishment of the Big Bang expansion cosmology about matter creation from basic particles to structure formation after the cosmic singular Big Bang.

This revolution, based on the combination of space satellite in-situ detection and plasma astrophysics, will establish a new plasma object cosmology, where the basic units constituting cosmic matter structures are plasma object "cells" of various scales formed under the combined action of Jeans gravitational instability and electromagnetic forces. Planets, stars, galaxies, and galaxy clusters and other local gravitational centers are the "hearts" of plasma object "cells" at corresponding scales, the "cell walls" are the boundary layers where corresponding plasma objects interact with surrounding cosmic interstellar environments, the plasma object current systems linking the "hearts" and "cell walls" are the "blood circulation" flowing within these "cells," and the plasma and its turbulent waves filling local interplanetary, interstellar, intergalactic, and intercluster cosmic spaces are the "muscles" of corresponding "cells." Therefore, in this new plasma cosmology, the structure of the universe is no longer isolated stars that can shine almost steadily, but active organic "cells" of various scales with flesh and blood and interconnections. Moreover, small-scale "cells" can form larger-scale "cells" through "blood vessel" links, and the entire observable universe is likely a large "cell" in expansion.

The third astronomical revolution caused by in-situ detection research of Earth' s magnetosphere and heliosphere space plasma with the advent of the human space age has also posed a series of challenging major scientific questions for astrophysics, especially plasma astrophysics. Here, we briefly list several urgent scientific questions that require in-depth research.

(1) **Origin of Cosmic Magnetic Fields and Existence of Magnetic Monopoles**: Modern astronomical observations have found that magnetic fields universally exist in cosmic space at various scales from planets and stars to galaxies and galaxy clusters. Moreover, based on analysis of Voyager satellite in-situ detection data that have crossed the heliosphere and entered interstellar medium, it appears that there may universally exist a continuous turbulent spectrum of plasma density and magnetic fields in cosmic diffuse media extending from cosmic object large scales to particle micro-dynamical scales [?, ?]. Whether overall magnetic fields at various scales of cosmic plasma objects or turbulent magnetic fields in

continuous media must play important roles in the formation and evolution of cosmic plasma object structures. Therefore, their origin issues will inevitably affect various periods of cosmic evolution and may even rewrite existing cosmic evolution history. For example, since the radiation field of the early hot universe has gradually decoupled from matter particles with cosmic evolution and survived to this day as cosmic microwave background radiation, whether the turbulent magnetic field of the early plasma hot universe could also survive through phase transitions during cosmic evolution and what role it played in later cosmic evolution are questions that need further clarification. If we further trace back to the very early evolution process of cosmic particle creation, whether the creation and annihilation of magnetic monopoles accompanied the evolution of the very early universe will also have extremely important impacts on the composition and astrophysical characteristics of existing cosmic matter [**?**].

(2) **Charge Distribution of Cosmic Plasma Objects and Net Cosmic Charge Problem**: In a completely balanced and uniform plasma environment, due to electrostatic shielding effects, net space charge distribution and corresponding scale perturbation electrostatic fields can only appear within the Debye radius scale. However, in a plasma object system with a gravitational center, the existence of large-scale charge distribution and electrostatic fields is entirely possible. For example, a star in an ideal static equilibrium state is actually a "charged" celestial body (e.g., the Sun' s net residual charge is about 77 C) [**?**, **?**, **?**, **?**, **?**]. Therefore, besides gravitational interaction, there is also electromagnetic interaction between stars, though it is negligible compared with gravity. However, for individual charged particles in stellar atmospheres, the electrostatic force they receive from "charged" stars is comparable to gravity (for protons) or even far greater than gravity (for electrons). Moreover, considering the actual non-uniform and non-equilibrium state of stellar atmospheres, the actual charge and electric field distributions are much higher than the static equilibrium values under ideal conditions. The charge and electric field distributions in cosmic "cell" plasma object systems must have important impacts on the dynamical processes of plasma media around gravitational centers, but this impact has been seriously neglected due to the long-standing wrong concept of star-centered dominance and neglect of interstellar medium effects. On the other hand, for existing observable cosmic matter, a widely accepted result is the extreme asymmetry between matter and antimatter, originating from the weak asymmetry of about 10^{-9} between particles and antiparticles during very early cosmic evolution. Since such weak asymmetry could exist between matter and antimatter particles in the very early universe, could there be similar "asymmetry" between baryons and leptons with positive and negative charges, respectively, so that the present observable universe might have an appropriate net residual charge as a whole? In fact, only an extremely weak asymmetry of 10^{-36} between baryons and leptons in the very early

universe could have significant impacts on the present observable universe structure, because electromagnetic force is now 10^{36} times stronger than gravity.

(3) **Formation and Evolution Mechanisms of Cosmic Plasma Object Current Systems**: The arrival of the space age has provided a new research method for astronomy: in-situ satellite detection research of space plasmas. It has not only discovered a large number of plasma object structures and current systems invisible to traditional astronomical observation methods but also completely updated human understanding of cosmic objects and their activity phenomena, gradually establishing a new plasma cosmology. Among them, the basic units constituting cosmic matter are plasma object "cells" separated by various magnetic plasma interfaces. The plasma object current systems that play crucial roles in the structure and evolution of these plasma object cells, linking celestial gravitational centers closely with surrounding interstellar media, not only serve as important bridges and links for the transmission and conversion of gravitational and electromagnetic energies in celestial systems but are also the most important key factors determining the structure, evolution, and eruptive activity phenomena of plasma object systems. Therefore, the formation mechanism and electrodynamical evolution of cosmic plasma object current systems are fundamental theoretical topics in plasma astrophysics and are issues that have not received due attention and have been seriously neglected so far.

(4) **Electrodynamical Problems of Cosmic Ray Origin and Transmission**: Cosmic rays, especially their charged particle components such as electrons and atomic nuclei, carry large amounts of charge and current, inevitably causing a series of electrodynamical responses in interstellar plasma media during their propagation through vast interstellar space. In fact, Alfvén pointed out as early as 1939 that, without considering interstellar medium responses, the maximum current that cosmic ray propagation can carry would not exceed the Alfvén limit of $17\gamma\beta$ kA due to self-generated current magnetic field limitations [**?**], where β and γ are the cosmic ray particle velocity normalized by light speed and the corresponding relativistic factor, respectively. However, if the electrodynamical response of the background interstellar plasma medium is considered, this Alfvén limit can be smoothly exceeded [**?**]. The response of interstellar medium to current-carrying cosmic ray propagation mainly has two aspects: first, interstellar magnetic fields can guide cosmic ray particles to transmit along magnetic field directions, forming field-aligned currents whose current-carrying limit can be far greater than the above Alfvén limit. Another electrodynamical response that breaks through the Alfvén transmission current limit is that the background plasma medium induces a reverse current to offset the current of cosmic rays themselves, greatly reducing the self-generated magnetic field of current-carrying cosmic rays [**?**, **?**, **?**]. In cosmic ray research, the main issues of concern are

still the production and propagation mechanisms of cosmic rays and their energy spectra, with little involvement in their interstellar space current-carrying transmission circuits and electrodynamical evolution. Based on basic plasma charge and current neutrality considerations, the interstellar space transmission of current-carrying cosmic rays cannot be an isolated high-energy particle propagation process but must exist as part of some large-scale cosmic plasma current circuit, or even just appear as an "excited state" of this cosmic current circuit. Their electrodynamical roles in various cosmic plasma current systems are also topics worthy of in-depth research.

(5) **Heating of Cosmic High-Temperature Plasma and Acceleration of Non-thermal High-Energy Particles**: Based on modern astronomical observations, 90% of observable cosmic matter is high-temperature plasma media diffused in vast cosmic spaces such as interplanetary, interstellar, intergalactic, and intercluster spaces. In the evolution process after decoupling of cosmic radiation components and matter particle components, radiation components have cooled with cosmic expansion to the present cosmic microwave background radiation temperature of only about 2.7 K, while matter particle components appear as high-temperature plasma states of X-ray thermal radiation sources, with corresponding heating mechanisms remaining unsolved mysteries [**?**]. In addition, observations of celestial eruptive activity phenomena show that non-thermal high-energy particles are the most universal products of eruptive activities and generally exhibit power-law energy distributions. Although research on their acceleration mechanisms has attracted widespread attention, mature and satisfactory theories are still lacking.

(6) **Origin of Dissipation and Structure Intrinsic Mechanisms in Cosmic Plasma Object Systems**: Since the establishment of thermodynamics, the "arrow of time" problem characterized by irreversibility has been haunting the basic theoretical system of complex system dynamical evolution in modern science from biological cells to cosmic objects. Although Boltzmann's "molecular chaos" hypothesis for collision processes temporarily masked the contradiction between classical Newtonian mechanics and classical statistical mechanics in classical system determinism, providing a formal bridge and cornerstone for the irreversibility of complex systems from "order" to "randomness." However, when encountering plasma object systems that are essentially complex systems connected by long-range interactions, the cornerstone of the "molecular chaos" hypothesis obviously cannot hold. Therefore, we must establish new intrinsic mechanisms for dissipation (randomization of ordered processes) and structure (ordering of random processes) in plasma object systems. Modern system theory, cybernetics, and information theory (or later dissipative structure theory, synergetics, and catastrophe theory) that emerged almost simultaneously with plasma astrophysics, called complex science, may provide us with some beneficial insights. The essential characteristic of complex science

> is the nonlinear interaction within systems. Within appropriate system parameter ranges, the evolution of nonlinear equations may exhibit sensitive dependence on initial conditions, causing originally deterministic systems to show unpredictable non-deterministic characteristics, called orbital chaos of complex systems [?]. If combined with the quantum mechanical uncertainty principle, this uncertainty fundamentally cannot be eliminated by improving experimental measurement precision, thus rising to become a basic principle of modern complex system science and laying a new cornerstone for the intrinsic mechanism of randomization dissipation in complex systems. On the other hand, for an open complex system far from equilibrium, under certain conditions it can also spontaneously form stable ordered structures through energy exchange with the outside world, namely so-called "self-organizing dissipative structures," providing a reasonable "organic" growth mechanism for the spontaneous formation of non-equilibrium dissipative structures in open systems [?, ?, ?]. In fact, in the modern plasma cosmology, plasma object systems as cosmic "cells" are typical open complex systems and are often in states far from equilibrium. Therefore, drawing on the system theory perspective of modern complex science to re-examine the origin of dissipation and structure intrinsic mechanisms in cosmic plasma object systems may help us more completely understand plasma object structures and their eruptive activity phenomena.

Finally, we would like to borrow a sentence from Mr. Lu Tan' s speech on "the origin of cosmic matter" : "The comparison between dark matter, dark energy and ether, blackbody spectrum is thought-provoking!" Indeed, similar to the two extremely uncoordinated clouds of "ether" and "blackbody spectrum" in the clear sky of physics at the end of the 19th century, modern astronomy has also encountered two prominent contradictions between theory and observation that are difficult to reconcile: "galaxy mass deficit" and "cosmic accelerated expansion." A widely circulated view holds that besides observable matter, the universe may contain large amounts of so-called "dark matter" and "dark energy" that only participate in gravitational interactions but not electromagnetic interactions. From the end of the 19th century to the early 20th century, people' s persistent search for "ether" and "blackbody spectrum" did not find traces of "ether" but led to the establishment of relativity and quantum theory, making great contributions to the development of modern science. Similarly, continuous exploration of "dark matter" and "dark energy" may also give rise to revolutionary new theories in contemporary astronomy, making important contributions to the development of plasma astrophysics and especially the establishment of plasma cosmology.

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