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The Gravitational Influence of Dark Matter on Exoplanets and Its Applications

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Abstract. Dark matter accounts for about 85% of all matter in the universe. Its existence is cross-verified by four independent types of astronomical evidence: galaxy rotation curves, the virial theorem, hydrostatic equilibrium, and gravitational lensing. This paper reviews the gravitational effects of dark matter on exoplanets and the applications of its existence in matter observations. A literature review and comparative analysis are used to examine the gravitational effects at three levels. At the microscopic level, dark matter particles and planets form quantized gravitational bound states, but the purely gravitational energy effect is extremely small. In terms of evolution, the gravitational lines of dark matter promote the birth of planetary systems. In terms of applications, heating signals, high-energy neutrinos, and spatial distribution mapping produced through the gravitational capture of dark matter by planets may provide new approaches to dark matter detection. The results also show that this approach has advantages in the amount of experimental data and sensitivity to low-mass dark matter. However, because the signals are weak, the dependence on models is strong, and the astrophysical backgrounds are complex, it is still at the stage of theoretical exploration. It supplements existing detection methods rather than replacing them.

Keywords: Dark matter exoplanets dark matter halos gravitational effects dark matter detection

1. Introduction

Dark matter accounts for the main part of the universe's matter [1]. It does not participate in electromagnetic interactions, cannot be observed with conventional electromagnetic radiation, but has gravitational effects. Without dark matter, many observed astronomical phenomena cannot be explained [2]. The evidence of its existence comes from multiple independent sources: the rotation curve of galaxies shows that the velocity of external objects remains high and constant at large radii, indicating the existence of invisible matter that provides additional gravity [2]. The virial theorem, hydrostatic equilibrium, and gravitational lensing have also inferred the total mass far exceeding that of the visible matter. These four independent evidences cross-verified the existence of dark matter.

There are three main detection methods: direct production of dark matter particles by colliders, detection of dark matter and nuclear scattering in underground laboratories, and indirect detection of annihilation products [3]. Direct detection requires deep underground shielding from cosmic rays; for example, China's Jinping Underground Laboratory is situated approximately 2,000 meters

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beneath the surface, where it waits to detect recoil signals from collisions between dark matter particles and atomic nuclei [4]. However, the actual signal is several dozen orders of magnitude higher than the target, and there is still no definitive discovery [4]. The positrons in the indirect detection exceed the annihilation or pulsar explanation of the available dark matter.Existing reviews focus on laboratory and satellite methods [1-4], and few discuss the relationship between dark matter and exoplanets from the perspective of gravity. However, the planet itself is located in the dark matter halo, and dark matter is both a prerequisite for planetary formation and may couple with individual planets through gravity.

The problem of dark matter spans fundamental areas of physics such as quantum mechanics, nuclear physics, particle physics, and stellar formation and evolution. This paper will proceed in three steps. First, it analyzes the gravitational effects of dark matter on exoplanets at three levels: macroscopic halo fields, microscopic bound states, and formation and evolution. It then discusses the applications of these gravitational effects in dark matter detection. Finally, it compares them with mainstream methods. Its main significance is to provide a preliminary assessment of the idea of gravitational effects of dark matter on exoplanets and their applications.

2. Gravitational effects of dark matter on exoplanets and planetary systems

2.1. Dark matter halo environment of planetary systems

The visible stars of the Milky Way are surrounded by a huge dark matter halo, whose mass far exceeds that of luminous matter [2, 3]. The Sun moves around the Galactic center at about 220,000 meters per second. Calculations show that maintaining this orbit requires about 10^{11} solar masses of matter within the Sun's orbit, while the mass of visible stars and gas is only about one-tenth of this amount [1, 4]. This missing mass is precisely the gravity of the dark matter halo [3, 4]. In terms of the principle of velocity measurement, the rotation curves mentioned above are measured through the Doppler effect. A blueshift in spectral lines corresponds to an object moving toward us, while a redshift corresponds to it moving away. The radial velocity can be calculated from the amount of spectral shift. Measurements of stellar velocities at different radii in galaxies revealed the anomaly that velocity does not decrease with radius. The mass of dark matter halos is confirmed through several independent approaches, such as the flattening of galaxy rotation curves [2], galaxy motion speeds and the virial theorem, the hydrostatic equilibrium of hot gas within galaxy clusters, and the deflection of light through gravitational lensing. All four lines of evidence point to the same conclusion: there must be non-luminous gravitational mass far exceeding the luminous matter. Cosmology further provides a quantitative picture. Based on Hubble's law and escape velocity, a critical density can be defined, while the density inferred from all luminous matter is only 3% of the critical density. The density of dark matter is currently estimated to be about 10 times that of luminous matter. On larger scales, the gravity of dark matter halos also affects the structure and fate of galaxies and even the universe [5]. Therefore, the most widespread and most certain effect of dark matter on exoplanets is produced through this macroscopic gravitational field. Every planet moves in a gravitational environment dominated by dark matter.

2.2. Gravitational capture and bound states of dark matter in planets

The two uncertainty relations of quantum mechanics are the starting point for all microscopic discussions. The product of the uncertainties in position and momentum is no less than one half of the reduced Planck constant. The product of the uncertainties in energy and time also has a lower

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limit. Under these relations, whether a particle's quantities take discrete or continuous values depends on whether it is confined within a small space. Particles confined at the atomic scale have discrete energy levels and must be described using quantum mechanics. Particles moving freely in open space have continuous energies and can still be treated using classical mechanics. The principle of probing microscopic structures also comes from quantum mechanics. The shorter the de Broglie wavelength of an incident particle, the smaller the structure that can be resolved, and the shorter the wavelength, the greater the kinetic energy required. The momentum transferred to the target during scattering is approximately equal to the reduced Planck constant divided by the probing scale. This is why high-energy particle beams are used to study atomic nuclei and even deeper structures. The gravitational coupling between dark matter and planets also needs to be understood within this logic of scale.

However, a complete framework of particle physics also requires relativity, because microscopic particles often move extremely fast. Quantum mechanics and relativity must be combined in the theoretical framework of quantum field theory. Quantum field theory provides two results that cannot be explained by quantum mechanics or relativity alone: the proof of the Pauli exclusion principle and the necessary existence of antiparticles. The physical interpretation of the negative-energy solutions in the Dirac equation was eventually confirmed by the discovery of the positron. If dark matter particles are microscopic particles, they also need to be understood within this framework.

From the perspective of the four fundamental interactions, gravity is the only force confirmed to act on dark matter. However, the mediator particle required for its quantum description has still not been discovered, and the microscopic coupling mechanism between dark matter and gravity itself remains unclear. It should also be noted that chemical bonds, van der Waals forces, and friction commonly found in the macroscopic world do not belong to the four fundamental interactions. Van der Waals forces are residual electromagnetic interactions between neutral molecules. Nuclear forces are residual strong interactions between quarks, while the action of gravity on dark matter belongs to a fundamental interaction itself, rather than some residual force. The general rule for transmitting interactions is that the greater the mass of the exchanged particle, the shorter the range of the force. The range is approximately equal to the reduced Planck constant divided by the product of the exchanged particle's mass and the speed of light. Photons have no mass, so the electromagnetic force has a long range. The W boson, which transmits the weak force, has a large mass, making the weak force short-ranged and weak. Dark matter carries neither electric charge nor color charge, and does not participate in electromagnetic or strong interactions. Its difference from ordinary matter lies only in gravitational coupling [6].

According to their statistical properties, particles are divided into bosons and fermions. If the system's wave function remains unchanged after exchanging two identical particles, these particles are bosons. Their spin is an integer, and multiple bosons can occupy the same quantum state. Particles whose wave function changes after exchange are fermions, and their spin is a half-integer. They obey the Pauli exclusion principle, meaning that two identical fermions cannot occupy exactly the same quantum state. The spin and statistical properties of dark matter particles are not yet known. This directly affects whether they can accumulate densely in a planetary core and is another source of theoretical uncertainty. At a deeper level, Noether's theorem reveals a one-to-one correspondence between symmetries and conservation laws. Time translation corresponds to energy conservation, spatial translation corresponds to momentum conservation, rotation corresponds to angular momentum conservation, and gauge transformation corresponds to charge conservation. Particle reactions must also satisfy conservation laws such as baryon number and lepton number

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conservation. If dark matter particles participate in some unknown interaction, these conservation laws may further restrict the forms of detectable signals.

3. Applications of gravitational effects: Planets as dark matter detectors

Planets can use their own gravitational fields to collect dark matter. If non-gravitational interactions exist between dark matter and ordinary matter, particles passing through a planet can lose energy through scattering, become captured, and accumulate in its core [7]. Particle–antiparticle annihilation converts all rest mass into energy, with an efficiency far higher than nuclear fusion. If dark matter particles are their own antiparticles, the thermal energy produced by the annihilation of dark matter accumulated in the core will heat the planet, appearing as an infrared excess. The temperature will be higher than the level expected from stellar irradiation and tidal heating alone. From a methodological perspective, particle physics relies on three methods to investigate unknown particles: scattering experiments, analysis of decay products, and the energy spectra of bound states. Planetary detection corresponds to the latter two approaches. The discovery of new signals must also rely on statistics. The discovery of the Higgs particle shows that a single event does not constitute evidence, and a large number of samples must be accumulated. Statistics must be built from the inferred mass distribution, and repeated cross-verification must be carried out. This method also applies to planetary detection.

Neutrinos produced by annihilation pass through planets with almost no loss, providing a channel for clean signals [3]. Neutrinos were predicted by Pauli based on the conservation of energy and momentum, and they participate only in weak interactions and gravity. Solar neutrinos pass out of the Sun almost immediately and serve as a detector for observing the real-time state of stellar interiors.

In addition, scattering between dark matter and atmospheric molecules can change atmospheric temperature and ionization equilibrium, which can be detected indirectly through transmission spectroscopy. The spectra of different molecules provide the basis for identifying the atmospheric composition of exoplanets. Planets are distributed throughout the Milky Way. By observing the anomalous heating of planets at different locations, it is theoretically possible to infer the local dark matter density and map the spatial distribution of the halo. This is also something that ground-based laboratories cannot achieve. Gravitational lensing mapping is complementary to this method. Astronomy cannot conduct controlled experiments, so planetary detection depends on large samples and long-term observation. Compact objects extend the same logic. Neutrons obey the Pauli exclusion principle, white dwarfs are supported by electron degeneracy pressure, and the upper mass limit of neutron stars is about 3.2 solar masses. Objects exceeding this limit collapse into black holes. Compact objects have higher densities, deeper gravitational potentials, and larger energy quanta, which may help future observations [6].

4. Conclusion

This paper reviews the gravitational influence of dark matter on exoplanets and its applications. First, at the macro level, the Milky Way and exoplanetary systems are all in the gravitational field of the dark matter halo, and dark matter provides the dominant background gravitational environment. Secondly, at the micro level, dark matter particles can form quantumized gravitational bound states with planets, but their pure gravitational energy effect is extremely weak; If dark matter exists in non-gravitational interactions, it may be captured by planetary gravity and accumulate in the core. Thirdly, at the level of formation and evolution, the gravitational effect of dark matter affects the

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birth and long-term dynamic evolution of planetary systems. At the application level, the heating signal produced by dark matter annihilation, high-energy neutrinos, and the method of inferring the spatial distribution of dark matter by abnormal heating of planets, It may provide a new way to detect dark matter and has the advantages of large sample size and potential sensitivity to low-mass dark matter, but it is still in the stage of theoretical exploration and can only supplement but not replace existing detection methods.

There are still shortcomings in this paper: the quantitative estimation of dark matter capture rate and heating signal is insufficient, the model dependence is strong, and the interference of astrophysical background is not fully discussed. In the future, high-precision infrared observations of nearby giant planets can be carried out, the observational upper limit of dark matter heating can be established, and more refined models of planetary interiors can be developed to enhance the testability of this method.

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