Analysis of Using the Light Pressure Effect to Drive Spacecraft under Complex Conditions

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Abstract.

Light pressure driving has attracted widespread attention due to its unique physical properties and potential in various scientific and technological fields. Due to the limitations of current technology and material levels, achieving a macro-level light pressure-driven approach in the short term is unrealistic. A wide range of research areas for light-pressure driving are focused on the micro level and suitable light-pressure materials. Under the current theoretical framework, a light pressure-driven spacecraft with suitable light sail materials is a highly competitive alternative for interstellar navigation. This article mainly simulates the process of light pressure-driven spacecraft accelerating to sub-light speed through laser irradiation on the Earth's surface and decelerating the returning spacecraft. The article comprehensively considered factors such as laser frequency, sail size, and spacecraft mass during the simulation process and provided simulation results under appropriate conditions. Due to the significant relativistic effect of this process, this paper also considered the red shift and blue shift effects of relativistic light in the simulation process.

Keywords: Light Pressure, red shift, blue shift, spacecraft

1. Introduction

Since Kepler discovered the phenomenon of light pressure in the 17th century, scientists have studied it for centuries and found that it has broad application prospects in both macro and micro. The most promising application direction of light pressure is to use the light pressure effect to drive spacecraft in the aerospace field [1]. However, light-pressure driving in a macroscopic state is unrealistic under current technical conditions. Common research directions are mainly in the microscopic field and suitable light-driven materials.

The main purpose of this article's research is to discuss possible driving methods for deep space exploration in the aerospace field and to perform theoretical calculations on its specific driving conditions. The article will be divided into two main parts. The first part will introduce the basic properties of light and the calculation results of the light pressure effect in simple cases. The second part will calculate the light pressure effect under complex circumstances, including the redshift effect during acceleration and the blue shift effect during deceleration, and analyze and discuss the light pressure effect under various circumstances based on the calculation results.

At present, the speed of common spacecraft is generally below 20km/s, and practical manned interplanetary travel in the solar system needs to reach $1*10^4\,\mathrm{km/s}-1*10^5\,\mathrm{km/s}$. Interstellar travel requires a flight speed of at least 10% of the speed of light to be feasible, which means that the speed of our spacecraft needs to be several orders of magnitude higher than currently [2]. Because the light-pressure spacecraft can accelerate for a long time, it is extremely valuable for greatly increasing its speed.

2. Basic knowledge

2.1 Basic principles of light pressure

Light pressure is the pressure exerted by light on the surface of an object. Kepler first proposed it in the early 17th century to explain the reason why the tail of a comet faces away from the sun. Maxwell calculated the pressure of light incident on a black body in the 19th century through electromagnetic theory:

$$p=\frac{S}{c} \tag{1}$$

where S is the Poynting vector of light and c is the speed of light.

When the object completely absorbs the light shining on the surface of an object, its light pressure is p. When the light is completely reflected, its light pressure is 2p. The light pressure in real situations is generally between these two values [3].

2.1.1 Wave-particle duality of light

The wave-particle duality of light reflects that light has both wave and particle properties. This theory is based on Planck and Einstein's light quantum theory and shows people that there is a unity of wave and particle properties in physical reality.

2.1.2 Particle nature of light

The particle nature of light was first proposed by Newton. Due to Newton's great achievements in the past and his admiration, Newton's light particle theory received much attention from the scientific community for a long time after it was proposed. However, the theory was later challenged by Thomas Young and others. But at the end of the 19th century, Hertz's discovery of the photoelectric effect reaffirmed the particle nature of light [4]. To a large extent, the light pressure effect also depends on the particle nature of light.

Photons have many properties similar to ordinary particles, such as momentum and energy. The energy of a single photon is determined by its frequency:

$$E = h\nu \tag{2}$$

Where E is the photon's energy, ν is the photon's frequency, and h is Planck's constant.

According to Einstein's theory of relativity:

$$E = mc^2 \tag{3}$$

Based on the momentum formula, the momentum of a photon is expressed as:

$$p = mc \tag{4}$$

From this, this paper can get the relationship between photon frequency and momentum:

$$p = \frac{h\nu}{c} \tag{5}$$

2.2 Simple light pressure effect

Light pressure is the behavior of photons transferring their momentum to an object, much like the collision of macroscopic objects. Since light has a particle nature, it has momentum $\frac{hv}{c}$, which generates impulse on the object's surface during its interaction with the object, thereby generating pressure. Light pressure occurs when many photons continuously and steadily illuminate a substance [5].

Assume that the frequency of the monochromatic light shining on the object is v, and the number of photons shining on the unit area per unit time is n, then the light intensity is:

$$I = nh\nu \tag{6}$$

If the photons are all reflected after contacting the interface, their momentum will remain unchanged, and the direction will be opposite. Therefore, the impulse received by the ΔS area in Δt time is $2nh\nu\Delta t / c$. . According to the momentum theorem:

$$2nh\nu\Delta S / c = \overline{F}\Delta t \tag{7}$$

Therefore, the average pressure $\overline{F}$ is:

$$\overline{F} = 2nhv\Delta S / c \tag{8}$$

The average pressure $\overline{P}$ is:

$$\overline{P} = \frac{\overline{F}}{\Delta S} = 2nh\nu / c \tag{9}$$

The total pressure F is:

$$F = \overline{PS} = 2nh\nu S / c \tag{10}$$

Above is a simple light pressure formula derived from the particle nature of light [6].

2.3 Redshift and blue shift of light waves

The article just introduced the particle nature of light and the characteristics of light pressure, but it should not ignore the wave nature of light. Light also has typical characteristics of waves. For example, under the Doppler effect, the wavelength of light will change accordingly. This phenomenon is called red shift or blue shift of light.

2.3.1 Lightwave Red Shift Effect

The redshift effect of light waves refers to the phenomenon that the wavelength of light becomes longer due to the influence of certain effects. From the observer's perspective, the frequency of the light becomes lower, and the wavelength becomes longer. Redshift effects can be divided into three main types: Doppler redshift, gravitational redshift, and cosmological redshift. Doppler redshift is caused by the relative motion between the observer and the radiation source, gravitational redshift is caused by the work done by photons overcoming the gravitational field, and cosmological redshift is caused by the expansion of space that causes stars to move away from each other. Among them, gravitational redshift only has obvious effects around neutron stars or black holes, and cosmological redshift plays a dominant role on the scale of 100 million parsecs, so this article mainly discusses the Doppler redshift effect [7]. The size of the red shift is the redshift value z, which is defined as:

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{f_0 - f}{f} \tag{11}$$

Among them, $\lambda_0$is the original wavelength of light, f_0 is the original frequency of light, λ is the wavelength of light observed by the observer, and f is the frequency of light observed by the observer. It is not difficult to see that in the case of redshift, $z > 0$. In the case of relativity, the complete Doppler effect formula is:

$$1 + z = \frac{1 + vcos(\theta) / c}{sqrt(1 - v^2 / c^2)} \tag{12}$$

For the case where the object's motion direction is consistent with the observer ($\theta = 0$), the formula can be simplified as:

$$1+z=\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} \tag{13}$$

Since in interstellar deep space exploration, the angle between the Earth and the direction of motion of the detector is extremely small ($\theta \approx 0$), this paper can approximately use this formula to perform calculations [8].

2.3.2 Lightwave blue shift effect

The blue shift effect of light waves refers to the phenomenon that the wavelength of light becomes shorter due to the influence of certain effects. From the observer's perspective, the frequency of light becomes higher, and the wavelength becomes shorter. In astronomy, the main phenomena that can produce blue shift are the Doppler and gravitational effects. Corresponding to the redshift effect, Doppler blue shift is caused by the relative motion between the observer and the radiation source, and the gravitational redshift is caused by the positive work done by photons in the gravitational field. For the same reason as the redshift, this paper mainly discusses the Doppler blue shift effect, whose corresponding blue shift value $isz < 0$, and the others are consistent with the Doppler redshift formula [9].

3. Light pressure effect under complex conditions

3.1 Light pressure effect under red-shift conditions

3.1.1 Operation theory

Under normal circumstances, the acceleration caused by light pressure is far from enough to overcome the Earth's gravity. Hence, people need to use traditional launch methods, such as rockets, to transport the light-pressure spacecraft to a location where the celestial body's gravity is small enough, and then launch lasers from the ground. Promote the movement of the spacecraft so that the light pressure effect can better propel the spacecraft. After arriving at the predetermined location, the spacecraft opens its light sail to receive lasers emitted from the ground and propel it forward [10]. The specific calculation process needs to be combined with the formula given above.

3.1.2 Model Construction

Assume that the frequency of the monochromatic laser illuminated on the light sail is ν_0, the number of photons illuminated on the unit area per unit time is n, the size of the light sail is S, and the total mass of the spacecraft is m. The acceleration of the laser illuminated on the stationary light sail a_0 is:

$$a_0 = \frac{F_0}{m} = 2nh\nu_0 S / mc \tag{14}$$

When the speed of the spacecraft is v, with the spacecraft as the observer, the frequency ν of the laser is:

$$\nu = \frac{\nu_0}{z+1} = \nu_0 \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}} \tag{15}$$

At this time, the acceleration magnitude a is:

$$a = \frac{F}{m} = 2nh\nu S / mc = 2nh\nu_0 \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}} S / mc \tag{16}$$

According to Newton's formula of motion:

$$a = \frac{dv}{dt} \tag{17}$$

Combined with the previous formula, it can get:

$$\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} dv = 2nh\nu_0 S / mc \bullet dt \tag{18}$$

Integrated, it can obtain:

$$2carctan\left(\frac{\sqrt{c+v}}{\sqrt{c-v}}\right) + \frac{(v-c)\sqrt{c+v}}{\sqrt{c-v}} + v_0 = 2nh\nu_0 St / mc \tag{19}$$

Since the final flight speed is much greater than the initial speed, the initial speed can be approximately regarded as 0. C is a constant that balances the equation such that when t=0, v=0. By further processing the equation, it can get:

$$\frac{2carctan\left(\frac{\sqrt{c+v}}{\sqrt{c-v}}\right) + \frac{(v-c)\sqrt{c+v}}{\sqrt{c-v}} + C}{2nh\nu_0 S / mc} = t \tag{20}$$

This equation is too complex to have an analytical solution by ordinary calculation methods, but some numerical solutions can be calculated. The corresponding model can be constructed and calculated [11].

3.1.3 Operation results

Based on the model deduced and established above, this paper performed corresponding simulation operations and obtained some operating results.

Under the conditions of laser frequency $\nu_0 = 3.846 * 10^{14} Hz$, light sail area $S = 10^6 m^2$, and spacecraft mass $m = 10kg$, this paper adjusts the number n of photons irradiated on the unit area per unit time to increase the speed of the spacecraft. Gradually accelerate to $2.7*10^8 m/s$ (about 0.9 times the speed of light), record the time elapsed on the spacecraft at each speed, and draw figure 1.

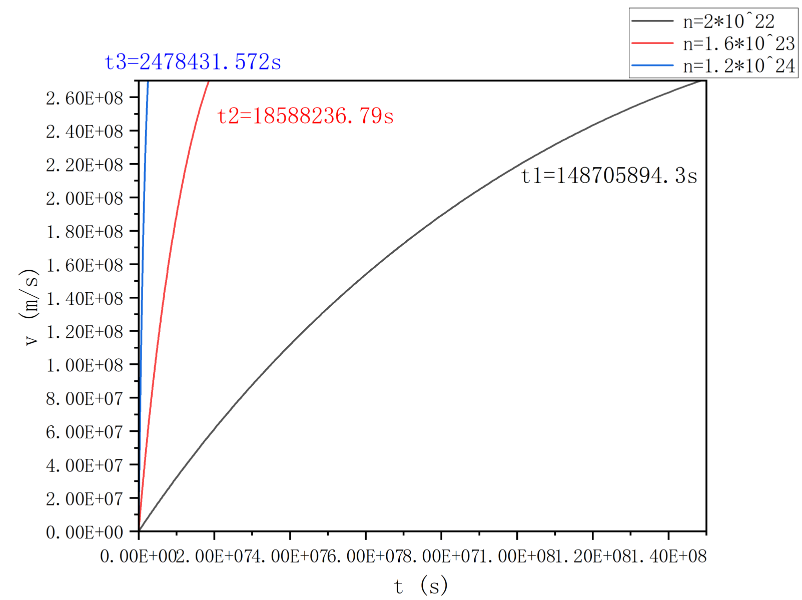

Fig. 1 Elapsed time on the accelerated spacecraft under different photon numbers n (Photo/ Picture credit: Original)

It can be seen from Figure 1 that when $n = 2*10^{22} s^{-1} m^{-2}$, the acceleration time on the spacecraft is about $1.49*10^8 s$ (about 1721 days). When $n = 1.6*10^{23} s^{-1} m^{-2}$, the acceleration time on the spacecraft is about $1.86*10^7 s$ (about 215 days). When $n = 1.2*10^{24} s^{-1} m^{-2}$, the acceleration time on the spacecraft is about $2.48*10^6 s$ (about 28 days). It can be seen that increasing the number of photons can very effectively improve the acceleration efficiency of the spacecraft. Therefore, the laser must increase the number of photons emitted simultaneously to improve the acceleration efficiency.

The number of photons it illuminated on the unit area in the unit time is $n = 2*10^{22} s^{-1} m^{-2}$, the area of the light sail is $S = 10^6 m^2$, and the spacecraft's mass is $m = 10kg$. Under these conditions, this paper adjusts the laser frequency $\nu_0$to gradually accelerate the spacecraft speed to $2.7*10^8 m/s$ (about 0.9 times the speed of light) and records the time elapsed on the spacecraft at each speed so that get the following Figure 2.

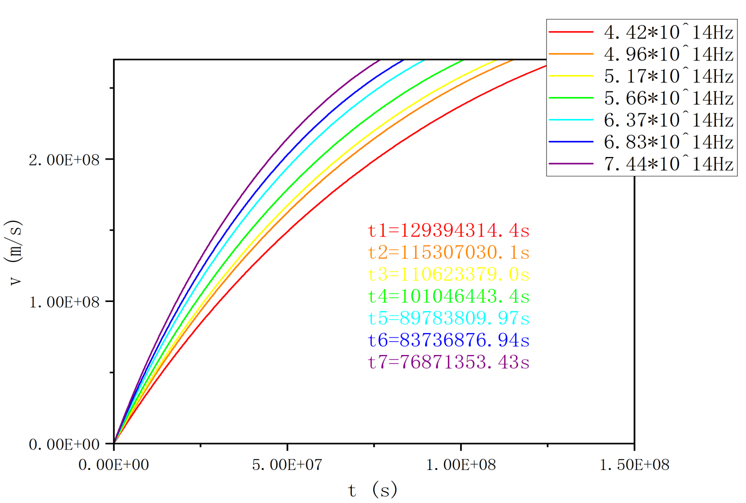

Fig. 2 Elapsed time on the accelerated spacecraft under different laser frequencies ν_0 (Photo/

Picture credit: Original)

From Figure 2, it can be seen that in the process from $\nu_0 = 4.42*10^{14} Hz$ to $\nu_0 = 7.44*10^{14} Hz$, the acceleration time on the spacecraft gradually decreases from about $1.29*10^8 s$ (about 1498 days) to $7.69*10^7 s$ (about 890 days). It can be seen that increasing the laser can improve the acceleration efficiency of the spacecraft, but the effect is limited. If higher-frequency invisible light is used as the laser source, the acceleration efficiency should continue to improve.

The number of photons this paper illuminated on the unit area per unit time is $n = 2*10^{22} s^{-1} m^{-2}$, the laser frequency $\nu_0 = 3.846*10^{14} Hz$, and the mass of the spacecraft $m = 10kg$. Under the conditions, this paper adjusts the light sail area S to gradually accelerate the spacecraft speed to $2.7*10^8 m/s$ (about 0.9 times the speed of light), record the time elapsed on the spacecraft at each speed, and draw the following figure 3.

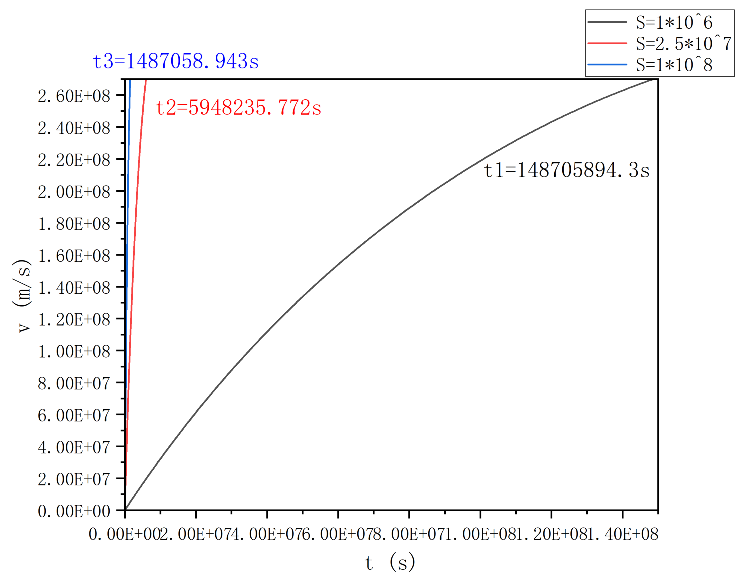

Fig. 3 Elapsed time on the accelerated spacecraft under different light sail area S (Photo/ Picture credit: Original)

It can be learned from Figure 3 that when the light sail area $S = 1*10^6 m^2$, the acceleration time on the spacecraft is about $1.49*10^8 s$ (about 1721 days). When $S = 2.5*10^7 m^2$, the acceleration time on the spacecraft is about $5.95*10^6 s$ (about 69 days). When $S = 1*10^8 m^2$, the acceleration time on the spacecraft is about $1.49*10^6 s$ (about 17 days). It can be seen that increasing the area of the light sail can very effectively improve the acceleration efficiency of the spacecraft, and this method is less technically difficult and more economical than increasing the number of photons n. Therefore, increasing the light sail area can greatly improve the acceleration efficiency and is relatively simple.

The number of photons this paper illuminate on unit area in unit time is $n = 2*10^{22} s^{-1} m^{-2}$, laser frequency $\nu_0 = 3.846*10^{14} Hz$, light sail area $S = 10^8 m^2$, adjust the mass m of the spacecraft so that the speed of the spacecraft gradually accelerates to $2.7*10^8 m/s$ (about 0.9 times the speed of light), and record the time elapsed on the spacecraft at each speed, and draw the following figure 4.

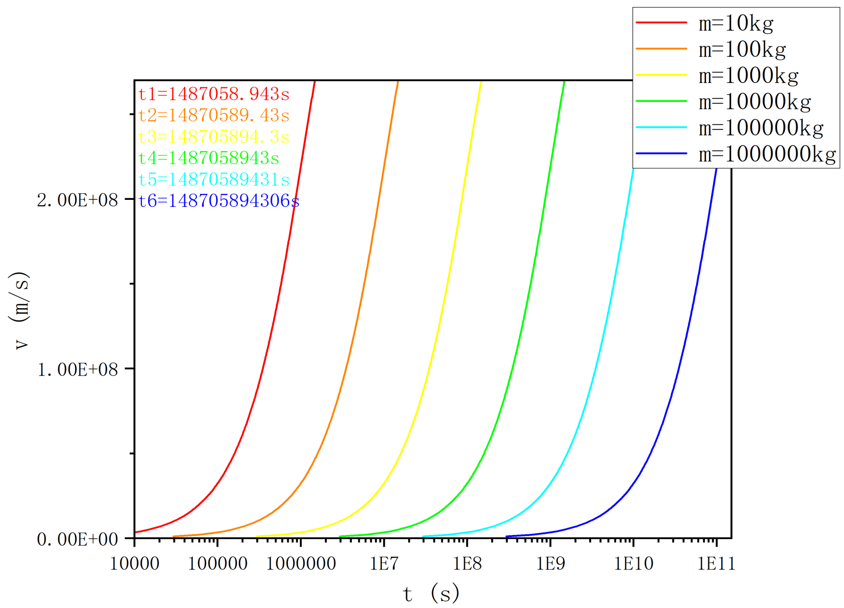

Fig. 4 Elapsed time on the accelerated spacecraft under different spacecraft masses m (Photo/Picture credit: Original)

It can be learned from Figure 4 that in the process from $m=10kg$ to $m=1*10^6 kg$, the acceleration time on the spacecraft increases from about $1.49*10^6 s$ (about 17 days) to $1.49*10^{11} s$ (about 1,721,131 days, 4,715 years).

It can be seen that increasing the quality of the spacecraft will lead to a significant decrease in the acceleration efficiency of the spacecraft, but increasing the payload can increase the number and types of tasks that the spacecraft can perform. In this regard, a choice must be made based on the situation.

3.2 Light pressure effect under blue shift conditions

3.2.1 Operation theory

For the spacecraft returning to the Earth, the light pressure effect can also be used to slow down the spacecraft by emitting laser beams from the Earth so that it can land on the Earth or enter low-Earth orbit. During this process, the laser beam received by the spacecraft will undergo a blue shift effect [12]. The specific calculation process needs to be combined with the above formula.

3.2.2 Model Construction

Assume that the frequency of the monochromatic laser illuminated on the light sail is ν_0, the number of photons illuminated on the unit area per unit time is n, the size of the light sail is S, the total mass of the spacecraft is m, and the propagation direction of the laser beam is the positive direction. The acceleration a_0 of the laser irradiated on the stationary light sail is:

$$a_0 = \frac{F_0}{m} = 2nh\nu_0 S / mc \tag{21}$$

When the speed of the spacecraft is v, with the spacecraft as the observer, the frequency ν of the laser is:

$$\nu = \frac{\nu_0}{z+1} = \nu_0 \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} \tag{22}$$

At this time, the acceleration magnitude a is:

$$a = \frac{F}{m} = 2nh\nu S / mc = 2nh\nu_0 \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} S / mc \tag{23}$$

According to Newton's formula of motion:

$$a = \frac{dv}{dt} \tag{24}$$

Combined with the previous formula, it can get:

$$\sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}} dv = 2nh\nu_0 S / mc \bullet dt \tag{25}$$

After integration:

$$\sqrt{c-v}\sqrt{c+v} - 2c\arctan\left(\frac{\sqrt{c-v}}{\sqrt{c+v}}\right) + C = 2nh\nu_0 St / mc \tag{26}$$

C is a constant used to balance equations. By further processing the equation, it can get:

$$\frac{\sqrt{c-v}\sqrt{c+v}-2carctan\left(\frac{\sqrt{c-v}}{\sqrt{c+v}}\right)+C}{2nhv_0S/mc}=t \quad (27)$$

This equation is too complex to have an analytical solution by ordinary calculation methods, but some numerical solutions can be calculated. Based on this, the corresponding model can be constructed and calculated.

3.2.3 Operation results

Based on the model deduced and established above, this paper performed corresponding simulation operations and obtained some operating results.

Under the conditions of laser frequency $v_0=3.846*10^{14}Hz$, light sail area $S=10^6m^2$, and spacecraft mass $m=10kg$, this paper adjusts the number n of photons irradiated on the unit area per unit time to increase the speed of the spacecraft. The size decelerates from $2.7*10^8m/s$ (about 0.9 times the speed of light) to 0, the time elapsed on the spacecraft at each speed is recorded, and the following figure 5 is drawn.

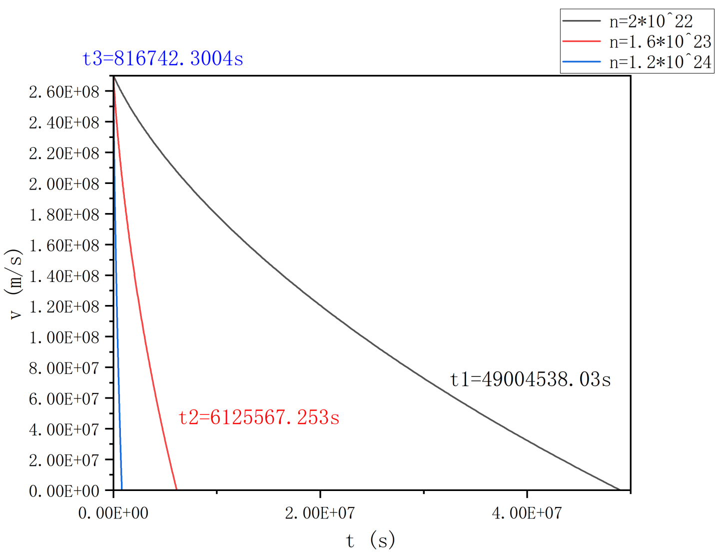

Fig. 5 Elapsed time on the decelerating spacecraft under different photon numbers n (Photo/Picture credit: Original)

It can be seen from Figure 5 that when $n=2*10^{22}s^{-1}m^{-2}$, the deceleration time on the spacecraft is about $4.90*10^7s$ (about 567 days). When $n=1.6*10^{23}s^{-1}m^{-2}$, the deceleration time on the spacecraft is about $6.13*10^6s$ (about 71 days). When $n=1.2*10^{24}s^{-1}m^{-2}$, the deceleration time on the spacecraft is about $8.17*10^5s$ (about 28 days). It can be seen that increasing the number of photons emitted by the laser can very effectively improve the deceleration efficiency of the spacecraft, and compared with the acceleration process under the same circumstances, the deceleration process takes only about one-third of the time. Therefore, the laser needs to increase the number of photons emitted simultaneously to improve the deceleration efficiency, and the deceleration process is significantly faster than the acceleration process.

The number of photons it illuminated on the unit area in the unit time is $n=2*10^{22}s^{-1}m^{-2}$, the area of the light sail is $S=10^6m^2$, and the spacecraft's mass is $m=10kg$. Under the conditions, this paper adjusts the laser frequency v_0 to decelerate the spacecraft speed from $2.7*10^8m/s$ (about 0.9 times the speed of light) to 0, record the time elapsed on the spacecraft at each speed, and draw the following Figure 6.

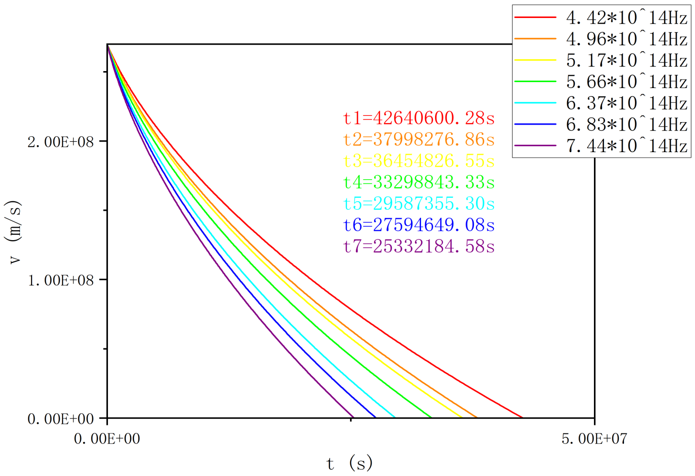

Fig. 6 Elapsed time on the spacecraft decelerating under different laser frequencies ν_0 (Photo/Picture credit: Original)

It can be seen from Figure 6 that in the process from $\nu_0 = 4.42*10^{14} Hz$ to $\nu_0 = 7.44*10^{14} Hz$, the deceleration time on the spacecraft gradually decreases from about $4.26*10^7 s$ (about 493 days) to $2.53*10^7 s$ (about 293 days). It can be seen that increasing the laser can improve the deceleration efficiency of the spacecraft, but the effect is limited. Compared with the acceleration process under the same conditions, deceleration takes only about one-third of the time. If higher frequency invisible light is used as the laser source, the deceleration efficiency should continue to be improved.

The number of photons it illuminated on the unit area per unit time is $n = 2*10^{22} s^{-1} m^{-2}$, the laser frequency $\nu_0 = 3.846*10^{14} Hz$, and the mass of the spacecraft $m = 10kg$. Under the conditions, this paper adjusts the light sail area S to decelerate the spacecraft speed from $2.7*10^8 m/s$ (about 0.9 times the speed of light) to 0, record the time elapsed on the spacecraft at each speed, and draw the following Figure 7.

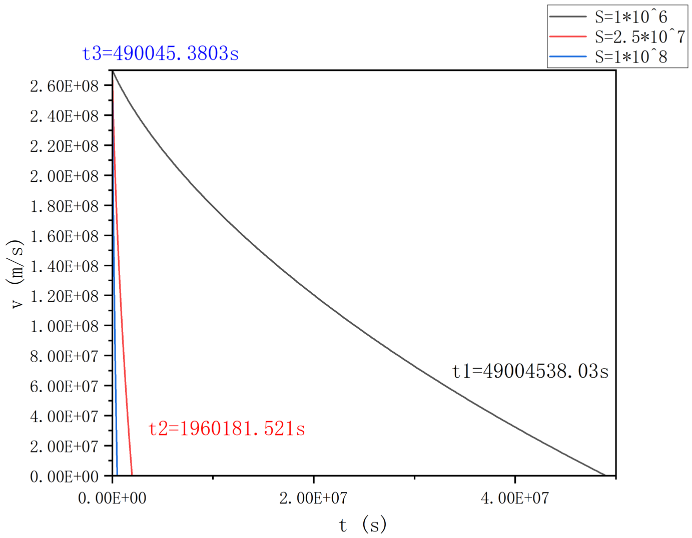

Fig. 7 Elapsed time on the decelerating spacecraft under different light sail area S (Photo/Picture credit: Original)

It can be seen from Figure 7 that when the light sail area $S = 1*10^6 m^2$, the deceleration time on the spacecraft is about $4.90*10^7 s$ (about 567 days). When $S = 2.5*10^7 m^2$, the deceleration time on the spacecraft is about $1.96*10^6 s$ (about 23 days). When $S = 1*10^8 m^2$, the deceleration time on the spacecraft is about $4.90*10^5 s$ (about 6 days). It can be seen that increasing the area of the light sail can very effectively improve the deceleration efficiency of the spacecraft, and this method is less technically difficult and more economical than increasing the number of photons n. Compared with the acceleration process under the same conditions, deceleration takes only about one-third of the time. Therefore, increasing the light sail area can greatly improve the deceleration efficiency and is relatively simple.

The number of photons this paper illuminates on the unit area in unit time is$n = 2*10^{22} s^{-1} m^{-2}$, laser frequency $\nu_0 = 3.846*10^{14} Hz$, light sail area $S = 10^8 m^2$. Under these conditions, this paper adjusts the mass m of the spacecraft so that the speed of the spacecraft decelerates from $2.7*10^8 m/s$ (about 0.9 times the speed of light) to 0, record the time elapsed on the spacecraft at each speed, and draw the following figure 8.

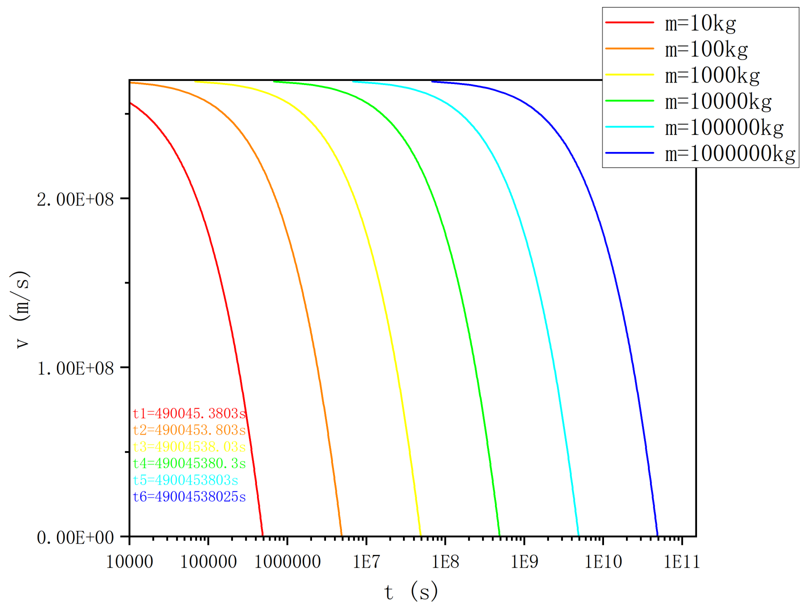

Fig. 8 Elapsed time on the decelerating spacecraft under different spacecraft masses m (Photo/Picture credit: Original)

It can be seen from Figure 8 that in the process from $m = 10kg$ to $m = 1*10^6 kg$, the deceleration time on the spacecraft increases from about $4.90*10^5 s$ (about six days) to $4.90*10^{10} s$ (about 567182 days, 1554 years). It can be seen that increasing the quality of the spacecraft will lead to a significant decrease in the deceleration efficiency of the spacecraft, but increasing the payload can increase the number and types of tasks that the spacecraft can perform. In this regard, a choice must be made based on the situation. Compared with the acceleration process under the same conditions, deceleration takes only about one-third of the time.

4. Conclusion

Through the above analysis and model simulation process, the following conclusions can be drawn: Increasing the number n of photons irradiating the unit area per unit time, the laser frequency ν_0, and the light sail area S can all improve the acceleration and deceleration efficiency of the light pressure spacecraft. Among them, increasing the number of photons n and increasing the area S of the light sail can better improve the acceleration and deceleration efficiency, and the technology of increasing the light sail is simple and more economical. If you need to increase the laser frequency ν_0 for a better lifting effect, use invisible light with a higher frequency. Increasing the spacecraft's mass will significantly reduce its acceleration and deceleration efficiency. Still, since spacecraft with larger payloads can complete more complex tasks, this aspect needs to be analyzed in detail based on the actual situation. Under the same circumstances, the deceleration time is about one-third of the acceleration time, indicating that the blue shift effect makes the corresponding process faster than the corresponding process of the redshift effect. The reference system used in this article is the reference system where the spacecraft is located. Later, further analysis and research on the model with the Earth as the reference system can be considered to obtain more practical results. The research and application of this article mainly focus on the use of light-pressure spacecraft in the space environment in the future. It is hoped that the practical application of this technology can come as soon as possible.

References

[1] Santi G, Favaro G, Corso A J, et al. Multilayers for directed energy accelerated light sails. Communications Materials, 2022, 3(1): 16.
[2] Zhang T, Chang H, Wu Y, et al. Macroscopic and direct light propulsion of bulk graphene material. Nature Photonics, 2015, 9(7): 471-476.
[3] Yang M, Ren K F, Gou M, et al. Computation of radiation pressure force on arbitrary shaped homogenous particles by multilevel fast multipole algorithm. Optics letters, 2013, 38(11): 1784-1786.
[4] Purdy T P, Yu P L, Peterson R W, et al. Strong optomechanical squeezing of light. Physical Review X, 2013, 3(3): 031012.
[5] Chen X, Kislyakov I M, Wang T, et al. Photoacoustic 2D actuator via femtosecond pulsed laser action on van der Waals interfaces. Nature Communications, 2023, 14(1): 2135.
[6] Levchenko I, Bazaka K, Mazouffre S, et al. Prospects and physical mechanisms for photonic space propulsion. Nature Photonics, 2018, 12(11): 649-657.
[7] Felicetti L, Santoni F. Nanosatellite swarm missions in low Earth orbit using laser propulsion. Aerospace Science and Technology, 2013, 27(1): 179-187.
[8] Lubin P. A roadmap to interstellar flight. ar**v preprint ar**v:1604.01356, 2016.
[9] Kulkarni N, Lubin P, Zhang Q. Relativistic spacecraft propelled by directed energy. The Astronomical Journal, 2018, 155(4): 155.
[10] Lubin P, Hettel W. The path to interstellar flight. Acta Futura, 2020, 12(9): 9-44.
[11] Sheerin T F, Petro E, Winters K, et al. Fast solar system transportation with electric propulsion powered by directed energy. Acta Astronaut, 2021, 179, 78–87.
[12] Atwater H A, Davoyan A R, Ilic O, et al. Materials challenges for the Starshot lightsail. Nature materials, 2018, 17(10): 861-867.