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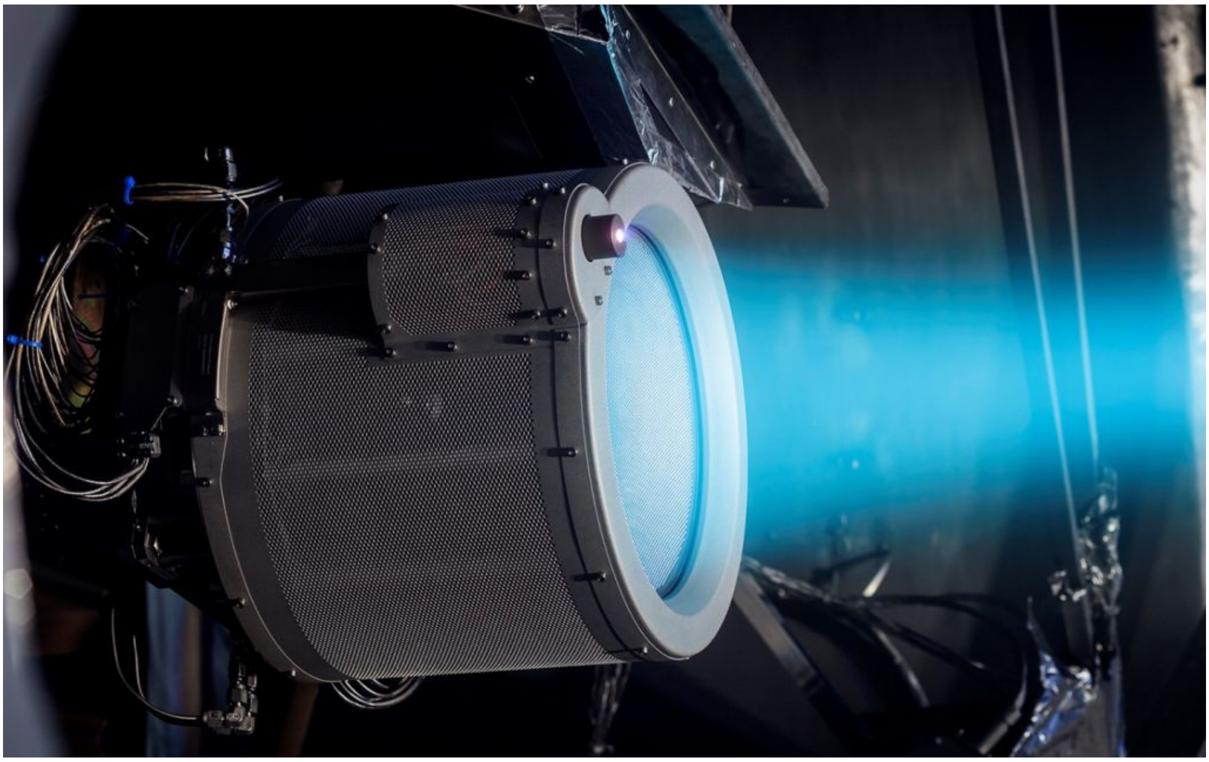
Ion Propulsion

Is ion propulsion the future of space and air transport?



T6 Ion Engine (QinetiQ, 2018)

Contents

Abstract

Ion propulsion has the potential to be a paradigm shift in the world of air and space travel. Silent, emission-free aircraft would combat the serious issue of climate change, as well as being cheaper to operate and less disruptive to those living around airports. The MIT 'Ion Drive' recently acted as a proof-of-concept for solid-state aircraft propulsion systems, travelling a 60m distance using only ion propulsion (Chu, 2018). There are currently no operational ion-powered aircraft since ion propulsion is incapable of providing high thrust and innovative solutions are needed for these systems to play a role in the future of propulsion. Spacecraft can also make use of ion propulsion systems, capable of exploring the universe in ways previously not possible. The Dawn spacecraft, for example, was able to explore two celestial bodies in one mission because of its ion propulsion system (NASA, 2019a); this would not have been possible with other propulsion systems. Whilst there are definite advantages to using these systems, the future of this technology lies in whether it is perceived to be of value to the space agencies and aircraft manufacturers with the capability to invest in it.

Introduction

First considered by Dr Robert Goddard in 1906 (Wright, 1999), ion engines have been used since the mid-20th century (Fig. 1) to manoeuvre satellites in space (Webb-Mack, 2018). Whilst this is an established technology, constant innovation is improving the reliability and usefulness of ion thrusters in space. The concept of ion powered aircraft has also been around for many years, however, the development of practical systems is slow and has not yet led to a functional product. Questions have been raised about the safety of systems using exposed wires carrying thousands, or even millions, of volts of electricity and whether prototype designs could be scaled up. Coppinger (2019) summarises this well; "The promise of ion propulsion is great but so is the level of voltage that is needed." Will we be flying on silent, fuel-free aircraft in the future? Could an ion thruster take humans to Mars? Or is ion propulsion economically impractical?

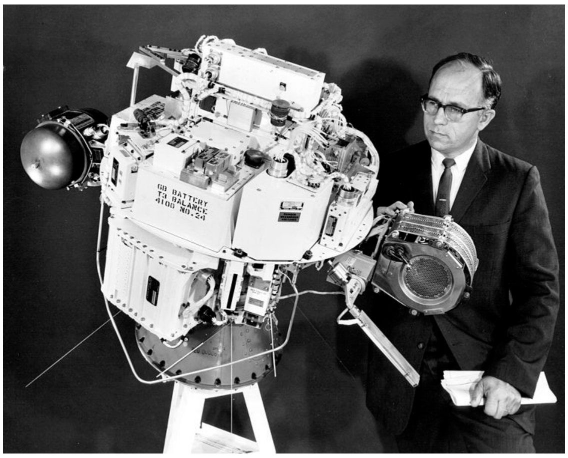


Fig. 1 The first satellite to use an ion engine, SERT-1 (NASA, 1954)

Ion thrusters use significantly less propellant than chemical propulsion systems, meaning that they cost less to launch. However, since they produce exceptionally little thrust, they are only suitable for use in space, where air resistance is negligible. This may seem impractical, considering the time it would take to accelerate a satellite to a suitable speed, however, ion thrusters are superior to their counterparts for certain missions. This is because they can accelerate to higher speeds, and produce very little vibrations. For example, BepiColombo is a European Space Agency mission to the planet Mercury which is using an ion engine propulsion system. Launched in October 2018, the craft is scheduled to arrive at Mercury in December 2025. Its thrusters ran from October 2018 to February 2019 and were turned on again in October 2019 (Clark, 2019). The thrusters accelerate the craft as well as acting as 'brakes' upon arrival to counteract the Sun's gravitational field. Whilst the use of ion propulsion was ideal for BepiColombo because of its long distance and sensitive instrumentation, the usefulness of this technology is dependent on the specific requirements of each mission. Put simply (Potterson, 2019) "the trade is made at a mission level, both [ion propulsion and chemical propulsion] have their advantages and disadvantages, so both have their place in the future of satellite propulsion."

Ion thrusters are best suited to spacecraft orbiting a planet, or travelling into deep space (Webb- Mack, 2018). Their high specific impulse (Research Review) can reduce travel time into deep space and extend mission duration for satellites in orbit. This reduces the cost of a mission and allows for the maximum research potential. However, their limited thrust means that for some missions, ion propulsion is likely to remain less useful than chemical thrusters. For example, a spacecraft travelling to the moon would prefer to use chemical thrusters which can accelerate and decelerate faster. Future developments in the performance of ion thrusters could give them a wider range of uses (Clark, 2019), although the same could be said for other space propulsion technologies. To be further developed, ion propulsion systems will need to demonstrate that they have more potential than other systems to improve the performance of spacecraft.

Using similar principles to ion thrusters, ion-powered aircraft use ion propulsion in the atmosphere, where the air acts as a 'propellant'. Recently, MIT claimed to have developed an aircraft that laid the foundations for a fully-electric solid-state passenger aircraft (Coppinger, 2019). This concept can not only be used for propulsion but also flight control, with 'plasma actuators' that could be used to replace mechanical flight control surfaces (Gregory, no date). The lack of moving parts makes an aircraft much more reliable and efficient, although this comes with many disadvantages relating to high voltage electricity storage, safety and reliability. There are many opinions relating to the usefulness of ion-powered aircraft, with the ultimate feasibility of the concept coming down to whether it could be made to be economically viable (RAeS, 2019).

Using ion propulsion on aircraft in the atmosphere would greatly reduce carbon emissions and noise around travel hubs, reducing the aviation industry's impact on climate change (Coppinger, 2019). This would make it more desirable to live near airports and would have other advantages in other sectors of aviation. For example, ion-powered high-altitude pseudo satellites (HAPS) would, theoretically, be able to continuously operate in the place of actual satellites at a lower cost. However, this technology is currently not in a developed state where it could be used on practical, profitable aircraft. Krauss (2019) believes that "it can be made into a commercial product in less than a year" although he explains that this is unlikely to happen. It is important to consider where future innovations may lead, and the potential of this technology to revolutionise air transport.

Research Review

Glossary

For continuity throughout this dissertation, all references to the following terms can be defined as follows:

Ion Propulsion	A method of propulsion which uses electromagnetism to accelerate ions to create thrust
Electric Propulsion (EP)	A method of propulsion which uses electromagnetism to accelerate ions to create thrust
Chemical Propulsion (CP)	In space, thrusters which burn propellant to create thrust
Ion Thruster	The broad term for ion propulsion systems in space
Gridded Ion Engine (GIE)	A type of ion thruster (Appendix A.1)
Ion-powered Aircraft, EAD Aircraft, Ionocraft	Aircraft which use ion propulsion

Ion Thrusters

Ion Thrusters can be used to propel satellites and spacecraft. They produce a little thrust in a very efficient way, using several methods. One of the most common types of ion thruster is the Kaufman Gridded Ion Engine (Appendix A.1). Another common type of spacecraft propulsion is chemical propulsion, which burns propellant to produce thrust. Ion propulsion generally produces less thrust but is more efficient than chemical propulsion (Potterson, 2019). This means that each propulsion method is best suited to different applications in space.

Specific impulse (I_{sp}) is a measure used to compare thrusters, defined as total impulse (Appendix A) divided by the mass of propellant used (NASA, 2015a). I_{sp} can be considered as an approximate measurement of how fast propellant is ejected from the vehicle; a propulsion system with a higher I_{sp} uses fuel more efficiently to create thrust. Having a higher I_{sp} means that propulsion systems can carry less fuel for a long journey, saving weight and cost. Ion thrusters usually have a higher I_{sp} than chemical thrusters since they eject propellant at a higher speed (Appendix A.1), making them more efficient even though they produce very little thrust (McGill School of Computer Science, 2007). Whilst ion thrusters eject very little fuel when thrusting, to maximise their specific impulse they require huge amounts of electrical energy, as opposed to the chemical sources of energy required by chemical thrusters (McGill School of Computer Science, 2007).

Ion thrusters have specific advantages over chemical thrusters when used on satellites. Dawn is a deep space probe operated by NASA (Fig. 3), which completed its mission in October 2018 and is now in an uncontrolled but stable orbit around the dwarf planet Ceres (NASA, 2019b). The spacecraft's three Kaufman GIEs required a total of 425kg of xenon propellant (NASA, 2019c). Though it took 4 days to accelerate from 0-60mph, the speed of the craft far surpasses the capabilities of any previous spacecraft (NASA, 2019c). The thrusters on Dawn ran for 51,583 flight hours (NASA, 2019c).

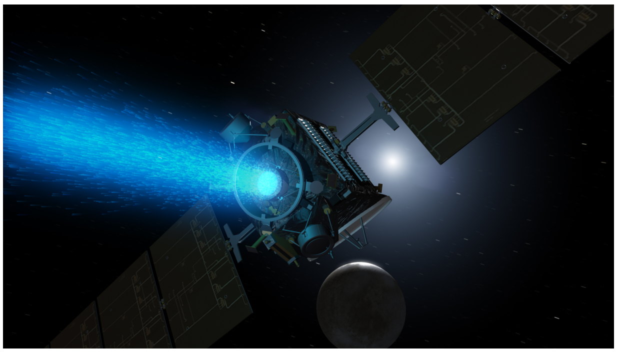


Fig. 3 Dawn (NASA, 2017a)

Another advantage of ion thrusters is their ability to enter and escape the orbit of smaller celestial bodies, such as dwarf planets and asteroids. The ability of ion thrusters to thrust for long periods with accurate thrusting control means that they can move spacecraft in ways which chemical thrusters cannot (NASA, 2019c). Dawn used this ability to study the asteroid Vesta and the dwarf planet Ceres in orbit. Previous spacecraft had only been able to perform flyby visits, which were not suitable for gathering much data. By orbiting Vesta for just over one year, the spacecraft could gather more data than before. Then its ion thrusters could bring it out of orbit to travel to Ceres, which it began orbiting three years later. NASA (2019b) noted three specific points of excellence relating to Dawn's ion thrusters:

- "First space mission to orbit two destinations"
- "Solar-electric propulsion system (SEPS) 2.7x faster than any previous spacecraft"
- "5.9 years of active, powered flight

Since the Dawn mission, NASA has continued to invest in ion propulsion systems, with modern-day thrusters capable of greater acceleration than before, meaning shorter journey times for future missions (Webb-Mack, 2018).

"The success of GOCE's ultra-sensitive gravity measurements depends on finely controlling the satellite's orbit and speed."

ESA (2009)

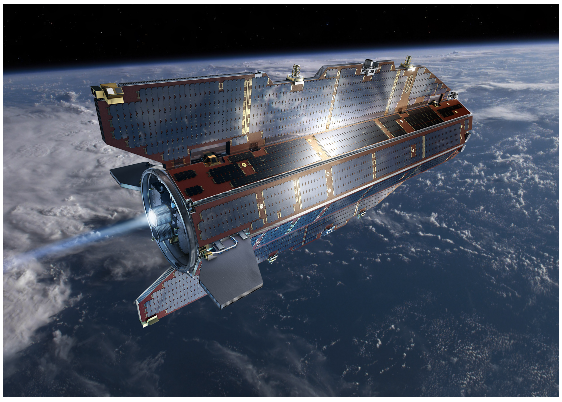
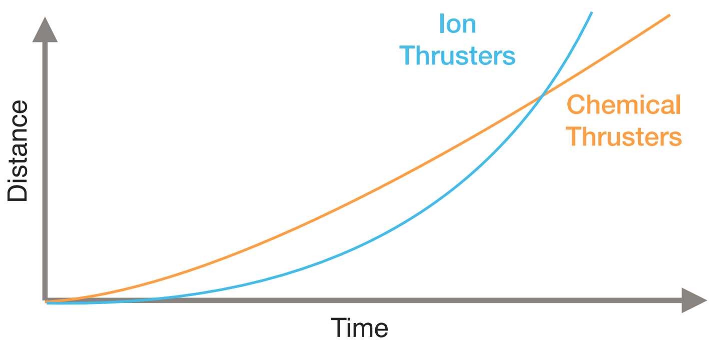


Fig. 2 GOCE (ESA, 2009)

To keep a satellite in orbit, delicate control of the position of the satellite is necessary, called orbital station-keeping (Intelsat, 2018). For this, and for controlling the attitude (rotation) of a satellite, ion thrusters are the most efficient and precise system. This is because their low thrust can be made accurate to 12µN, giving more accuracy than chemical thrusters. For example, a satellite with a high-gain antenna which must face a specific receiver on Earth could use ion thrusters to control its 'aim' much more accurately than one with chemical thrusters. An example of a mission which used ion propulsion for station keeping is GOCE (Fig. 2). This satellite, operated by ESA, was designed to map ocean currents and gravitational fields around the globe. To make suitable measurements, GOCE flew in an unusually low Earth orbit (ESA, 2009). Ion thrusters were used to keep the satellite in orbit against gravitational influences and air resistance in the upper atmosphere. Accurate movements of the satellite were possible with ion thrusters, which create almost no vibrational interference that could have otherwise led to errors in gravitational measurements (ESA, 2009). Additionally, the fuel lasted longer than expected, allowing for a longer mission duration without additional weight. The thrusters on GOCE ran for 36,000 flight hours (Clark, 2019) over 55 months, rather than the planned 20-month mission duration. Only then did the satellite run out of xenon fuel and de-orbit.

Fig. 4 Approximate distance-time graph for spacecraft propulsion systems



Ion thrusters are less suitable for missions to destinations such as the Moon because they accelerate too slowly. The craft would not be able to reach a high velocity before it would need to begin to slow down again to meet its destination (Potterson, 2019). As shown in Fig. 4, the slower acceleration of ion thrusters means that they take longer to reach nearby destinations than chemical propulsion. However, because they have a greater maximum speed, they can decrease travel time to destinations long distances away, in deep space.

Launching a 1kg payload into space can cost as much as 54,500 USD (Jones, 2018). Recently, companies such as SpaceX have reduced this to just 2,720 USD (Jones, 2018). However, this would still mean that a 1000kg satellite would cost over 2.5 million USD just to launch, alongside the cost of manufacturing and operating the satellite. This explains why saving weight is so important to spacecraft designers, from an economic perspective. A company setting up a satellite constellation would aim to design the lightest possible satellites since each additional kilogram costs thousands of pounds for each satellite. For a constellation of 1000 satellites, for example, adding 1kg to each satellite will result in a cost increase of at least 2.5 million USD. Because ion propulsion systems are so fuel-efficient, they can dramatically reduce the weight of a spacecraft, so reduce their cost.

Ion-powered Aircraft

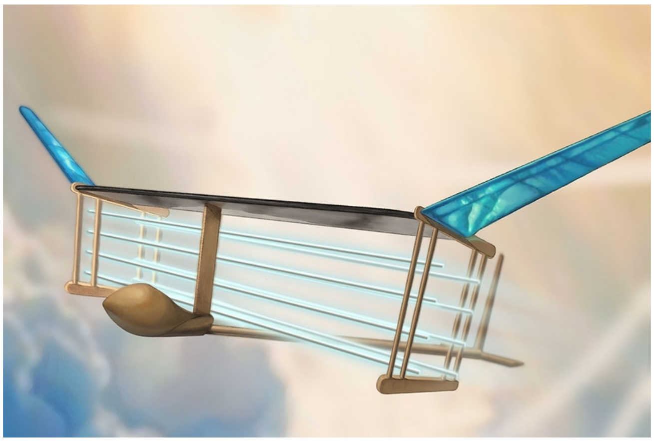


Fig. 5 'Ion Drive' (He, 2018)

There are many ion-powered aircraft designs, although the principles behind these systems are all the same. A high-voltage electrode ionises the air and the ions are attracted towards another electrode. As they move towards the second electrode, the ions collide with particles in the air and 'push' them away. The collective movement of these particles creates an 'ionic wind', and this is what creates the thrust to move the aircraft (Appendix A.2).

The first patent of an 'ionocraft' (Seversky, 1959) demonstrated that the ionic wind was capable of lifting a lightweight aircraft off the ground, although the power supply was external to the aircraft and remained on the ground during flight. Several independent hobbyists and professional organisations have since created new EAD aircraft (Krauss, 2018; Chu, 2018), although none have reached commercial success.

Ethan Krauss is the founder and president of Electron Air, LLC; the Electron Air 'lifter' carried its power supply in a flight in 2006, and was fully patented in 2018 (Krauss, 2019). Most EAD aircraft produce ozone and other harmful gases as a result of the ionisation process in air. However, by using thin (~2.5 micron diameter) emitter wires and carefully controlling current, Krauss (2019) explains that the production of ozone and the resulting loss of power can be reduced or avoided altogether. Additionally, his 'lifter' uses a negatively charged emitter electrode (Appendix A.2), which is more efficient and produces even less noise than similar designs. By using only micro-amps of current, the live wires are safe for use around humans (Electron Air LLC, 2019). Whilst touching them would give a person a painful shock as a result of the high voltage, it would not cause any serious harm (Krauss, 2019).

In 2018, Professor Stephen Barrett (MIT) successfully flew an electroaerodynamic (EAD) demonstrator aircraft (Fig. 5). The MIT aircraft flew 60 meters in 10 seconds, using a 40,000 volt power supply to create an ionic wind across eight pairs of wires (Coppinger, 2019). Early ion propulsion experiments demonstrated a thrust per unit power of 5N/kW, although Wilson, Perkins and Thompson (2009) stated that it may be possible to achieve 50N/kW, by reducing thrust and increasing voltage. In contrast, according to researchers at MIT (Chu, 2013), a jet engine works at only 2N/kW. Therefore, ion propulsion is a more efficient aircraft propulsion system. The main problem for scaling up this concept is that thrust density is proportional to the gap between the electrodes and the voltage. To lift a small aircraft and its power supply would require an impractically large air gap, or dangerously high voltage (Coppinger, 2019). The electrodes would either have to work at hundreds of thousands of volts or would need to encompass the entire aircraft. As a result of this, Wilson, Perkins and Thompson (2009) "concluded that the use of [ion propulsion] for aircraft propulsion did not seem very practical."

Other Applications of Ion Propulsion

Electroaerodynamics are not limited to primary propulsion systems; ion propulsion has many other applications. Plasma actuators using similar technology can be used instead of flight control surfaces. Where ailerons, elevators and rudders would be on an aircraft, two electrodes separated by a dielectric material can be used to adjust the properties of the wing and the lift it generates (Coppinger, 2019). This can be used to adjust roll, pitch or yaw (movement about all three axes). The wing could, therefore, be made smoother, with no moving parts, decreasing drag and improving reliability. The disadvantage and main reason this has not become popular is the reliance on an electrical control system. A computer or battery failure would render the aircraft uncontrollable, so a physical backup may be required (Barrett, 2018, quoted in Coppinger, 2019).

Barrett (2018, quoted in Coppinger, 2019) explains that future research may explore using the aircraft skin, possibly with electrodes embedded in it, to generate thrust (as opposed to drag). An aerodynamic boundary layer would not be allowed to grow, and the aircraft would be significantly more efficient. The boundary layer contributes to skin friction drag (NASA, 2015b), and so reducing its impact can increase aircraft efficiency. Barrett (2018, quoted in Coppinger, 2019) suggests that it would be possible to manipulate the electric fields around the aircraft so that the propulsion system controls the aircraft without the need for control surfaces. This way, the propulsion and control systems act as one, reducing the weight of the aircraft and using less moving parts. Again, much trust is being put in a wholly electrical power system. In counter-argument to this, though, many current aircraft use a 'fly-by-wire' system (Airbus, 2019) which relies on an electrical control system to move the aircraft, and so using ion propulsion in the place of physical flight surfaces would be no less reliable than this.

Ion Propulsion in Space

Existing Uses

Ion thrusters are useful on missions such as GOCE (Research Review), where accurate control is required in orbit without interfering with sensitive instruments. Chemical thrusters could not achieve the level of performance required by GOCE (ESA, 2009). The vibrations caused by chemical thrusters would have severely impacted the operations of sensitive instruments on-board the satellite (ESA, 2009). The ion engine on GOCE helped to control the satellite's orbit for 25 months longer than planned, proving that ion propulsion is useful to spacecraft (Clark, 2019). It positively impacted this mission by making it easier to take accurate measurements and extending the lifetime of the satellite to more than double its planned operational period.

Additionally, ion thrusters are currently useful in reducing travel duration and fuel requirements for most deep-space missions, such as with Dawn (Research Review). The distances involved with deep space missions means that ion powered spacecraft have the time to accelerate to much higher speeds, reducing mission duration compared to using chemical thrusters. It is ideal for a spacecraft to arrive at its destination as quickly as possible since the longer a spacecraft spends travelling in space, the greater the likelihood of mechanical failure. Chemical thrusters would require much more fuel to travel at similar speeds, increasing launch mass and cost. This means that ion propulsion is ideal for deep space travel, and is likely to remain the propulsion system of choice for such missions.

Whilst ion propulsion is more efficient than chemical propulsion, the limited thrust of an ion thruster means that it is not always the best option (Potterson, 2019), for example, ion thrusters are incapable of counteracting the Earth's gravity. For this reason, chemical propulsion is currently necessary for the launch vehicle to escape the atmosphere. Whilst future developments in ion thrusters may one day be able to offer this kind of service, it appears likely that chemical rockets will remain the most viable method of spacecraft launch.

Future Uses

Each propulsion system is selected on a mission-by-mission basis (Potterson, 2019) so both ion propulsion and chemical propulsion should be compared when designing a spacecraft. Future passenger- carrying spacecraft are amongst those spacecraft in development at the moment for transporting humans to destinations such as the Moon or Mars. When considering passenger-carrying spacecraft, one of the most important factors is the total mission time; the longer an astronaut spends in space, the greater exposure they have to UV radiation from the sun. Since manned missions are often over relatively short distances, ion propulsion cannot reach greater speeds than chemical thrusters before reaching their destination (Research Review). For this reason, using ion propulsion for manned missions would potentially put astronauts in danger of excessive exposure to UV radiation and could give them less time to study their destination (Potterson, 2019). Whilst it is important to consider all of the available options, in the case of human-carrying spacecraft, ion propulsion is simply not useful at the moment. Until an ion propulsion system can be developed that produces greater thrust, chemical thrusters are likely to remain the superior choice for manned missions.

It would be useful if one ion propulsion system could be used for launch, space travel, and landing, although that is currently not possible. Theoretically, with major innovation, an aircraft ion propulsion system could be adapted to utilise propellant in space, so that it would function in both the atmosphere and in a vacuum (Krauss, 2019). Different from existing ion thrusters, this would allow one propulsion system to be used for launch and operation. However, for an ion propulsion system to be developed for use in space and the atmosphere, it must first be proven that it is possible to create a commercially viable ion powered aircraft (see below). The main advantage of an entirely ion-powered spacecraft would be the lower weight and therefore lower cost (Research Review). If space travel becomes more popular in the future, an ion-powered launch vehicle would also reduce the environmental impact of burning tons of fuel for each launch.

Clark (2019) explained that to meet future demands, two key systems could be developed; in-orbit service satellites and debris removal. In orbit servicing means "small satellites that can latch on and maintain capability of large satellite[s]." (Clark, 2019) Ion propulsion would allow for the most accurate, efficient control of service satellites and could maximise their lifetime. This is a potential future application of ion propulsion which could play a major role in the satellites of the future. Debris removal combats the ever-growing issue of space 'junk'. There are more than 500,000 individual items of debris in orbit of the Earth being tracked by NASA (2017b), and there are millions of smaller pieces that could also seriously damage other satellites and spacecraft. Ion propulsion could help debris removal satellites to manoeuvre to intercept objects using less fuel than chemical thrusters, thus allowing them to operate for longer periods, collecting more waste (Fig. 6).

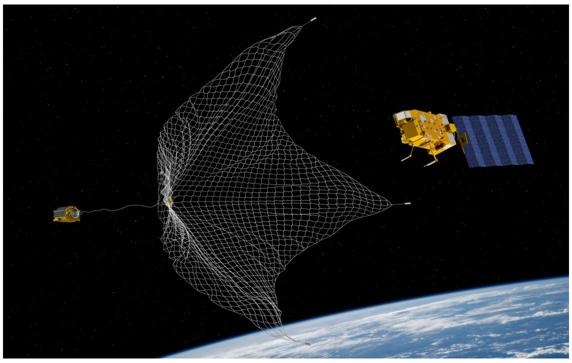


Fig. 6 e.Deorbit (Ducros, 2016)

Future Scope for Innovation

Maximising specific impulse, thrust and reliability are the main aims of engineers working to improve the usefulness of ion thrusters. Clark (2019) outlined a 'product road map' for electric propulsion in the future in which he discussed several aspects of ion thrusters which are open to future innovation, as explained in Appendix C:

1. *"Dual mode thrusters that can meet orbit raising and station keeping applications"*
2. *"Low cost, high volume market"*
3. *"Alternative manufacturing"*
4. *"Much longer life, looking at alternative materials and alternative propellants"*
5. *"High power, high thrust engines (10-50KW)"*
6. *"Low thrust applications for smaller satellites working in a constellation"*

Ion propulsion has a definite future in space, and it will likely become more useful over time.

Companies with experience in ion propulsion could develop it to become a more affordable, 'off-the-shelf' style propulsion system for lower-budget space organisations (Clark, 2019). There is certainly potential that ion propulsion systems could be extremely profitable in the future if current systems are improved. Ion thrusters are likely to be made more accessible to manufacturers, meaning that it is easier to procure an ion propulsion system. This means that the decision to use a specific propulsion system can purely be based on its practical advantages, rather than economic limitations.

Whilst there is significant scope for improvements to ion propulsion systems, there is likely a limit to their usefulness, specifically relating to their low thrust. The question remains as to whether this technology could be made superior to current chemical systems; it may become more viable to develop chemical propulsion systems than attempting to improve ion propulsion.

Economic Feasibility

Much of the future of ion propulsion lies in its economic viability. If companies are to develop the capabilities of ion propulsion, they need to be sure that it is economically viable for them to do so. Stakeholders such as space agencies and manufacturers don't have limitless budgets, and therefore need to be sure that the cost of developing this technology is outweighed by the economic and practical benefits. The advantage of using ion propulsion systems is that they reduce the weight of the spacecraft, meaning that it costs less to launch (Research Review). However, there will be additional costs as a result of using a 'new' propulsion system, since designers will need to spend more time working with the propulsion team to ensure that the spacecraft works together with the propulsion system.

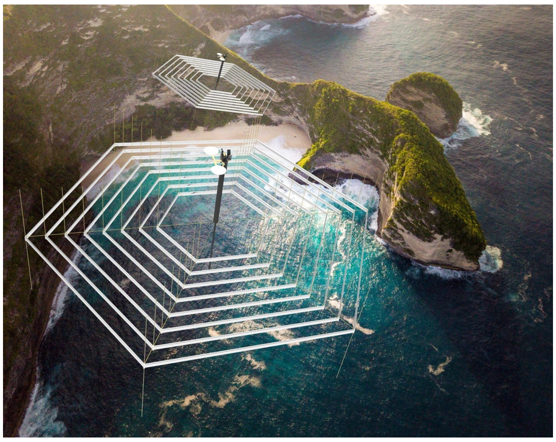
Manufacturers of ion thrusters such as QinetiQ must consider how much to invest in developing ion propulsion so that they can maximise their profits. It is important to manufacturers that they can achieve a greater return on investment than their costs, and it is challenging to understand where the balance is between spending too much and too little on product development. It is up to those companies to understand which aspects of this technology should be invested in so that the usefulness and profitability of ion propulsion can be maximised. Fundamentally, ion propulsion is currently economically viable for use in space and is likely to remain so (Clark, 2019). Whilst it cannot fulfil all needs of space propulsion systems, it is superior for many uses and certainly has a place in the future of space transport.

Ion Propulsion in the Atmosphere

Existing uses

There are currently two fundamental designs of ion-powered aircraft; either shaped like conventional aircraft or a more 'ufo-like' shape without wings. The advantage of the aircraft-like design is that, in the event of an electrical failure, the aircraft can glide safely to the ground. In contrast, an electrical failure on a wingless aircraft means that it would simply fall out of the sky. Existing ion-powered aircraft exist only as prototype designs, although it is hoped that they could one day be developed into functional products (Coppinger, 2019). Although he believes that his ion-powered aircraft (Fig. 7) could be made into a commercial product in less than a year, Krauss (2019) admits that it is likely to take much longer; "The quality will have to be improved, and the robustness... ...Extended flight times would also be helpful for the success of a commercial version." In reality, many more years of development and design are likely to be necessary for the development of a functional, practical and safe ion-powered aircraft.

Fig. 7 Multiple Ion Powered Crafts (Electron Air LLC, 2019)



Future Uses

Ion-powered aircraft have many potential applications in military and commercial aviation. These aircraft are nearly silent, zero-emission and invisible to infrared sensors. For this reason, air forces around the world could use ion propulsion in the future to fly stealth aircraft continuously for long periods. Barrett (2018, quoted in Coppinger, 2019) believes that this technology could be used on high-altitude pseudo-satellites (HAPS). These are aircraft which fly above 60km in altitude, performing tasks similar to satellites, but at a lower altitude and without the limitations of being in orbit (Stevens, 2019). A satellite in orbit can only remain above a single location on Earth if it is in geosynchronous orbit, whereas HAPS can circle over locations for long periods. As well as this, they can move with their target and are easier to reposition than satellites. Military applications include discreet surveillance and tracking, and commercially these could create communication 'bubbles' over major events or emergency aid efforts (Stevens, 2019).

On commercial aircraft, ion propulsion would reduce airport noise and air pollution dramatically. This would allow airports such as London Heathrow, which cannot land more than 5,800 flights between 23:30 and 06:00 each year (Heathrow, 2016), to continue operating silently at full capacity 24 hours a day. Alternative uses for ion propulsion systems include improving the aerodynamic efficiency of aircraft (Research Review). This would have both economic and environmental advantages, reducing carbon emissions and fuel costs for the airline.

Whilst these applications would have some social, economic and environmental advantages, we are a long way from functional ion-powered aircraft (Macheret, 2019). There are no companies currently designing a production aircraft, although Electron Air LLC is developing their designs with the end goal of commercialisation (Krauss, 2019). Ion powered aircraft have potential, although this technology is simply not developed to a suitable standard at the moment.

Future Scope for Innovation

For ion powered aircraft to become useful in the future, several issues must first be solved. In terms of the practical limitations of this technology, scaling up current designs in a way which allows them to carry a payload is difficult (Coppinger, 2019). This is because a larger, heavier aircraft requires greater thrust and so more electrodes or a higher driving voltage. Battery technology is also a problem for ion-powered aircraft since batteries powerful enough to sustain any reasonable duration of flight are very heavy. The Boeing 787 aircraft experienced problems with its relatively small batteries, resulting in heavy protective casings being needed to contain potential battery fires or explosions (Paur, 2013). Until advances have been made in battery technology, and the thrust of ion propulsion systems, there is little chance of a large aircraft using ion propulsion successfully.

Whilst jet turbine engines are tested to operate even when ingesting thousands of litres of water or hail, ion propulsion systems are much more vulnerable to weather conditions. Firstly, the wind will affect the performance and safety of lightweight aircraft; a practical aircraft should be able to fly even in the jet stream, which can reach wind speeds of 250mph (Britt, 2000). Additionally, rain or ice could affect the performance of an ion propulsion system by causing short-circuiting which would stop the generation of an ionic wind (Macheret, 2019). As a result, an ion-powered aircraft is likely to act unpredictably in adverse weather conditions. It is unlikely that the public would trust an aircraft using ion propulsion since uncontrollable factors including bird strikes or thermal degradation could cause a propulsion system failure by damaging the exposed, thin, high voltage wires (Macheret, 2019). Ultimately, three issues need to be investigated in the future before ion powered flight can be made feasible in outdoor conditions:

- Aircraft must be made large enough to remain unaffected by the wind
- Propulsion systems must function in heavy ice and rain
- The aircraft must be capable of remaining in controlled flight at all times, even in the event of structural damage

The safety considerations of an aircraft powered by high-voltage live wires are very different from
conventional jet turbine aircraft. To ensure passenger safety, it is important to ensure that the aircraft has been engineered so that no internal components could electrocute the occupants. Additionally, ground operations must not be affected by the presence of these electrodes. Ion powered aircraft could not be used near conventional aircraft since the high voltage wires create a serious hazard around flammable jet fuel (Macheret, 2019). Ground staff, passengers and other vehicles are all at risk when the aircraft is on the ground. Safety measures would need to be put in place to prevent damage to their aircraft or bodily harm to those around it and this makes it unappealing for airlines to adopt ion propulsion.

Whilst it may be possible to develop an ion-powered aircraft, the benefits of doing so are not likely to outweigh the amount of effort needed to develop, certify and operate something so different to existing aircraft. The development of so many technologies would be necessary to properly commercialise ion- powered flight that it is unlikely to be profitable for any single organisation to attempt to achieve this. Assuming worldwide governments certified the aircraft to fly, public trust in the new propulsion system would need to be developed before large masses would be willing to fly on the aircraft (Macheret, 2019).

Economic Feasibility

An ion powered aircraft would have a range of economic and practical advantages over other propulsion systems. Firstly, because no fuel is used, the cost of operating the aircraft is significantly reduced. Ion propulsion is a zero-carbon emission propulsion system, meaning that it would significantly reduce the environmental impact of aircraft. With global scientists and governments declaring ‘climate emergency’ (Brown, 2019), this kind of technology is likely to gain strong public support. As well as this, ion powered aircraft produce very little noise. Reducing the volume of aircraft around airports would please local residents, as well as increasing the capacity and revenue of airports (see Future Uses). The many military and commercial applications of ion propulsion make it potentially useful for development on aircraft.

However, several time-consuming, expensive developments are needed before ion propulsion will be suitable for use on aircraft. An ion powered aircraft would need to be designed from scratch and innovative solutions to the current limitations of the technology must be found. The aircraft must be manufactured, tested and certified by multiple aviation authorities. As well as this, a suitable means of manufacturing the aircraft must be developed, since specialist manufacturing processes are necessary for this unique technology. Assuming the aircraft is developed, aircraft operators such as airlines and air forces must then be convinced to purchase them.

The combination of these factors makes the development of ion powered aircraft risky. It would take a serious economic investment to bring this concept to life and a commercial failure could lead to bankruptcy. However, if a company succeeded in developing this technology, they could monopolise on it and have the potential to generate high profits as a result. Ultimately, though, the cost of developing this technology, combined with the high risk of failure, makes it undesirable. No companies are likely to pursue the development of ion-powered aircraft when other well-developed, safe means of propulsion exist (RAeS Specialist Propulsion Group, 2019).

This does not, however, mean that ion powered aircraft will never be made. Ion propulsion can also be used on aircraft wings to improve their efficiency (see Research Review). It would be less risky to develop ion propulsion for increasing the efficiency of aircraft, and this technology could likely be used on aircraft in the future.

Conclusion

Ion propulsion is already a part of space travel and looks set to remain in the future of space travel for some time. It is a useful technology, but only for certain missions (Potterson, 2019). The decision to use ion propulsion is likely to be based on its properties since many missions rely on certain thrust levels and specific impulses to be wholly successful. It is neither economically feasible nor practical to attempt to develop ion propulsion to be more useful than chemical propulsion for all applications. Therefore, whilst it is a useful technology, the future of space propulsion lies in a combination of both electric and chemical propulsion systems (Clark, 2019).

Fig. 8 Bird of Prey; aircraft of the future (Airbus, 2019)

Ion powered aircraft require significant development if they are to become a major part of air travel in the future. Currently, it is unlikely that commercialising an EAD aircraft would be economically feasible (Macheret, 2019). For that reason, one could assume that ion powered aircraft will not be ‘the future of air transport’. Motor-driven aircraft are already trusted by the public and have been proven to be economically viable. Airbus' 'aircraft of the future' (Fig. 8) uses electric motors (Airbus, 2019) rather than ion propulsion, indicating how ion propulsion is not perceived to be of any value to the aviation industry. Therefore, electric motors are much more likely to become the future of air transport than ion propulsion. However, with future innovations in other technologies (for example, with better battery technology and strong, light materials) the development of an ion powered aircraft should not be ruled out (Krauss, 2019; RAeS Specialist Propulsion Group, 2019). Additionally, ion propulsion has the potential to improve the efficiency of aircraft using other primary propulsion systems. There is an interest in developing ion propulsion but it will take time, persistence and investment.

It is important also to consider the social and environmental impact of this technology. Whilst it may not be profitable to develop ion-powered aircraft, in the wake of a global climate emergency (Brown, 2019) it could be perceived as a necessary technology for the future of humanity. Whilst companies may not choose to develop this technology to turn a profit, there are significant advantages to ion-powered aircraft that could be exploited to reduce the carbon emissions of the aviation industry, or as a solution to airport noise (Coppinger, 2019). Additionally, military development of this technology could be another driver against these economic barriers.

To summarise, ion propulsion will not solely be the future of air and space transport. However, it will play a role in the future of air and space travel. In space, ion propulsion is useful and will continue to be used, but it cannot currently compete with chemical thrusters for certain missions (Potterson, 2019). The future of atmospheric ion propulsion is less clear. With technological development, this technology could become a part of the future of air transport. However, ion powered aircraft are not likely to be able to compete with a jet turbine or electric motor driven aircraft. The RAeS Specialist Propulsion Group (2019) agrees that ion powered aircraft should be treated with scepticism, although we should remain mindful of Clark's three laws:

1. *"When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong."*
2. *"The only way of discovering the limits of the possible is to venture a little way past them into the impossible."*
3. *"Any sufficiently advanced technology is indistinguishable from magic"*

(Brander, 2019)

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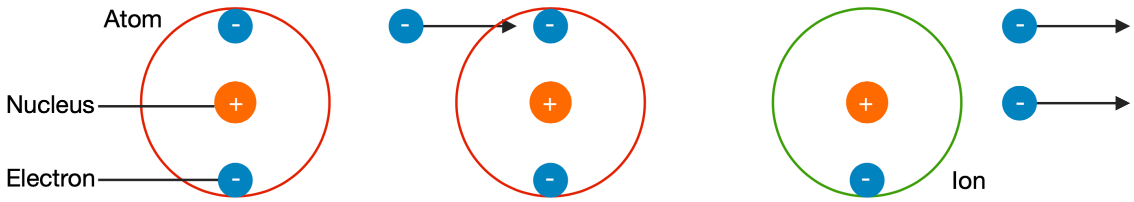
Appendix A
Technical Explanation

Charge is a property of matter. Objects can have either positive, negative or no charge. Opposing charges (i.e. positive and negative) feel an attractive force, whilst equally charged objects (e.g. positive and positive) repel each other (Breithaupt, 2015).

All matter is made up of atoms, which are collections of electrons and nuclei (made up of protons and neutrons). Electrons have a negative charge whilst nuclei are positively charged. Stable atoms include those in the air around us and atoms of propellant used on ion thrusters in space; a stable atom has a net (overall) charge of zero since its nucleus is charged by the same amount as its electrons. If an atom collides with a free electron (that is, one which is not a part of another atom), an electron is 'knocked' away from the atom. This loss of negative charge means that the atom becomes positively charged; this is called an ion (Breithaupt, 2015) (Fig. 1).

Fig. 1



To understand how ion propulsion works, an understanding of charge and ionisation is necessary, as well as an understanding of how propulsion systems work in general. The aim of a propulsion system is to change the velocity of a vehicle (McGill School of Computer Science, 2007). Since it is more difficult to change the velocity of a vehicle of greater mass, the effectiveness of a propulsion system can be considered using momentum, mv (mass x velocity). Impulse is the amount of change in momentum and the goal of propulsion systems is to create an impulse, which changes the velocity of a vehicle.

In order to 'create' momentum and increase in speed, another mass must be released with momentum in the opposite direction of travel (Breithaupt, 2015). Therefore, a rocket must carry with it some mass to eject in order to push itself forward, called a reaction mass. The impulse 'created' by launching a reaction mass away from a vehicle (spacecraft or aircraft) is equal to mv, the product of the reaction mass and its ejection velocity relative to the vehicle. The momentum of the vehicle then increases by this amount so its velocity increases by mv/M, the momentum of the reaction mass, divided by the mass of the vehicle. From this, it is clear that the acceleration of a vehicle can be maximised by increasing the reaction mass or ejection speed, or by decreasing the overall mass of the craft. These equations are simplified for the purposes of this explanation.

Whilst the net momentum of a vehicle and its reaction mass is conserved, the kinetic energy of the vehicle (i.e. its 'movement energy') changes since it has increased in speed. This energy must have a source and, in the case of ion propulsion, this is electrical (McGill School of Computer Science, 2007). Solar panels or batteries power the electrical mechanism required to accelerate the reaction mass to a suitable speed, increasing the speed of the vehicle. A way to measure the effectiveness of a propulsion system is using specific impulse. This is the impulse generated divided by the mass of propellant used and is similar to the speed at which propellant left the thruster. A propulsion system with a greater specific impulse uses propellant to create thrust in a more efficient way.

A.1 Kaufman Gridded Ion Engine

The Kaufman Gridded Ion Engine is a common type of ion thruster. The Ion Engine first uses a hollow discharge cathode to produce electrons (Fig. 2). A material is heated to above 1000oc, triggering a process known as thermionic emission (Clark, 2019). Electrons are liberated

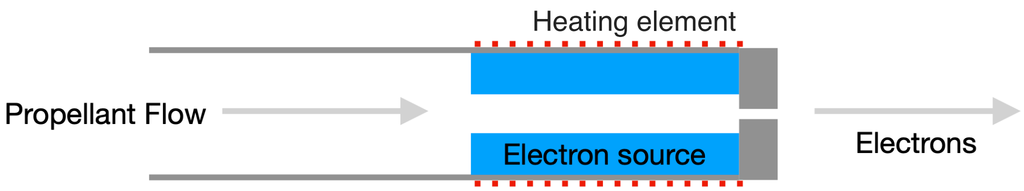
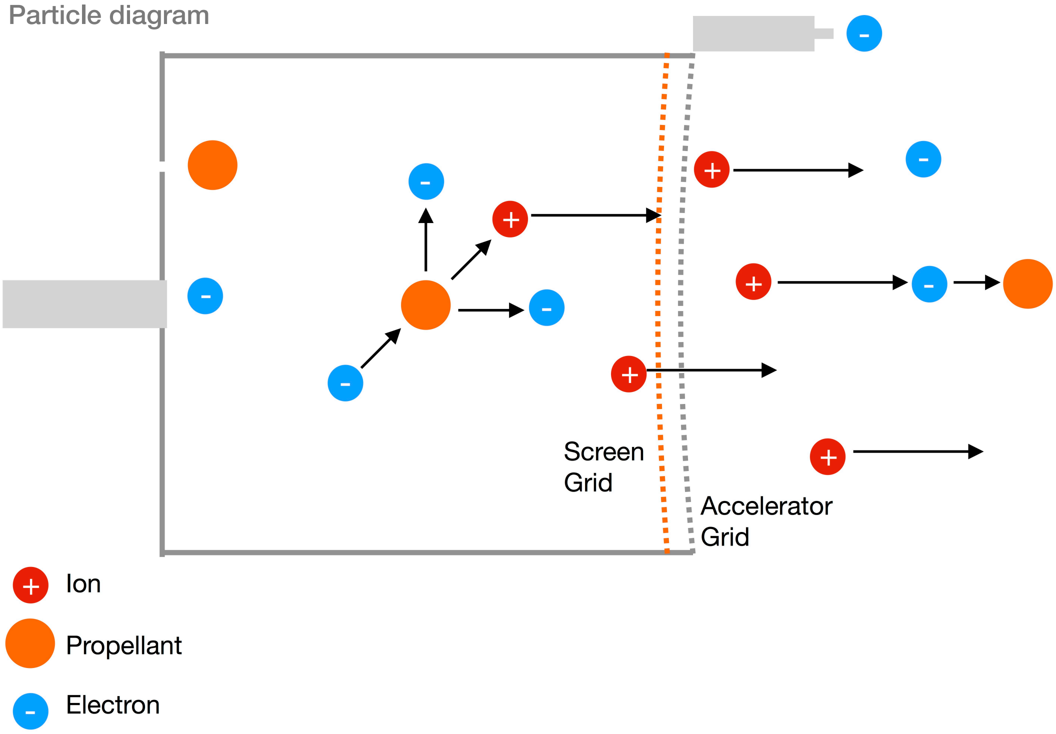


Fig. 2 Hollow discharge cathode

from the surface of the material and enter the ionisation chamber through a baffle, which disperses the electrons throughout the chamber. The electrons meet the main propellant flow in the ionisation chamber (Fig. 3). When propellant atoms collide with electrons, the atoms are ionised. The charged ions are accelerated through a molybdenum screen grid which has a very high positive voltage passing through it, and they then pass through an accelerator grid with a high negative voltage. The screen grid accelerates ions out of the thruster by attracting them, and then the accelerator grid repels them to prevent them from re-entering the thruster in a process called electron backstreaming. Having left the thruster, the ions are neutralised using another cathode. The ions absorb electrons and become atoms with no charge, moving away from the thruster at very high speeds. If the ions were not neutralised, their charge would cause them to be attracted back onto the thruster or the spacecraft. This would negate any thrust created by the ion engine (Clark, 2019).

Fig. 3 Particle diagram



Ion thrusters often use xenon as a propellant because it is inert, so won't react with any other materials in the thruster. Xenon is also dense, taking up a comparatively small volume for its reaction mass (Clark, 2019). However, even moving in excess of 140kms^{-1} (NASA, 2004), the momentum of these atoms is extremely low as a result of the extremely low mass of an atom. This means that the corresponding impulse acting on the spacecraft is also very low and so acceleration cannot occur quickly (Potterson, 2019). The force exhibited by an ion thruster is approximately equivalent to the weight of a standard A4 piece of paper in the Earth's gravity (Meacham, 2014). As explained by McGill School of Computer Science (2007):

> "To reach a given velocity, one can apply a small acceleration over a long period of time, or one can apply a large acceleration over a short time. Similarly, one can achieve a given impulse with a large force over a short time or a small force over a long time. This means that for manoeuvring in space, a propulsion method that produces tiny accelerations but runs for a long time can

produce the same impulse as a propulsion method that produces large accelerations for a short time. When launching from a planet, tiny accelerations cannot overcome the planet's gravitational pull and so cannot be used."

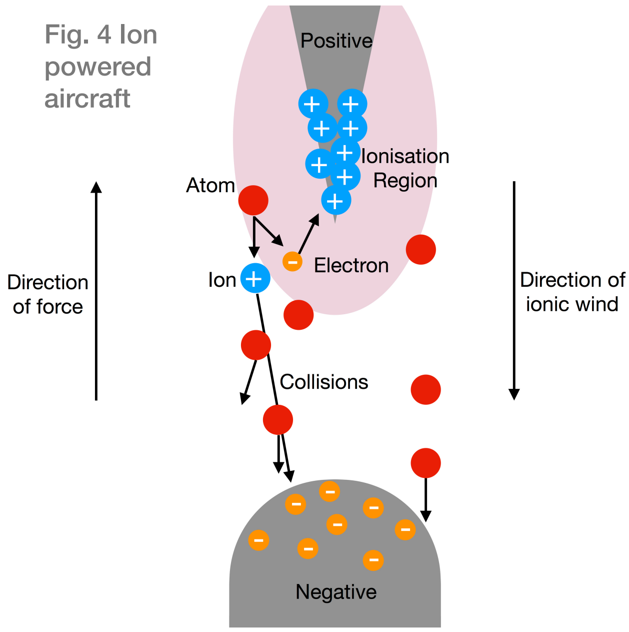
Because an ion thruster does not produce a high acceleration, it cannot be used for the launch of spacecraft from Earth. However, it is still capable of reaching extremely high speeds in a very efficient way once in space. Additionally, the thrust of an ion thruster can be controlled to within ±12mN (Clark, 2019). In comparison, conventional chemical thrusters propel more propellant at a slower speed by burning a propellant and oxygen mixture. This creates a larger force, but limits their maximum speed and accuracy, making them suited for a wide range of applications including the launch of vehicles from Earth (Potterson, 2019).

A.2 Ion-powered Aircraft

Two electrodes are connected to a high voltage power source. Importantly, one of these electrodes must end at a sharp point facing the other electrode, which must be more rounded and flatter. This is easiest to explain by assuming that the positive electrode is sharper, and the negative electrode is flatter. There is a small air gap between the two electrodes. When the power source is turned on, the high voltage causes the movement of electrons from the positive electrode to the negative electrode. This causes equal, opposing charges to build up on each electrode. On the sharper electrode, the positive ions are more densely packed into the small volume of the point, whereas the rounded electrode spreads its negative electrons across its surface. Where the charged particles are closer together on the sharp electrode, the electric field is stronger and the smoother electrode will therefore exhibit a weaker electric field since its charges are spread over a larger area. The strong electric field around the sharp electrode is capable of ionising the air, creating a 'cloud' of positive ions and negative electrons. The sharp electrode attracts the electrons and repels the ions. As a positive ion moves towards the smoother, negative electrode it collides with neutral atoms in the air. These collisions cause the atoms in the air to move in the direction of the ions, towards the negative electrode. This creates the ionic wind, and a force on the device pushing in the direction of the positive electrode (Dufresne, 2011).

This also works by using a sharper negative electrode and a rounded positive electrode, moving in the direction of the sharper (negative) electrode. The mechanics behind this option are more complicated, but there have been claims that this can be quieter and more efficient than the more common configuration using a sharp positive electrode (Krauss, 2019).

Fig. 4 Ion powered aircraft



Appendix B
Technical Analysis

Ionic Wind Speed

I used basic energy calculations (Macheret, 2019) to demonstrate the potential ionic wind speed and consider the mathematical limitations on ion-powered aircraft.

Nomenclature:

KE	Kinetic Energy (J)
KE_D	Kinetic Energy Density (Jm^{-3})
U_E	Electric Field Energy Density (Jm^{-3})
V_{MAX}	Maximum Ionic Wind Velocity (ms^{-1})
E_{MAX}	Maximum Electric Field Strength (Vm^{-1})
ρ	Density (kgm^{-3})
ε_0	Vacuum Permittivity (Fm^{-1})
V_B	Breakdown Voltage (V)
d	Distance Between Electrodes (m)

Equations:

I re-arranged the equations for kinetic and electric field energy density to find an equation for the maximum ion wind velocity. This assumes that the atoms in the air and the ions move at the same velocity.

$$KE_D \leq U_E$$

The kinetic energy density of the ionic wind cannot be greater than the energy density of the electric field.

$$KE_D = 1/2\, \rho \cdot V_{MAX}^2$$

$$U_E = 1/2\, \varepsilon_0 \cdot E_{MAX}^2$$

$$V_{MAX} = \sqrt{(\varepsilon_0 \cdot E_{MAX}^2/\rho)}$$

At STP:

$\varepsilon_0 \approx 8.85 \times 10^{-12}$
$\rho \approx 1.225$
$E_{MAX} \approx 3.4 \times 10^6$

ε_0 is a constant
I used a US standard value for density (Archer and Saarlas, 1962).

I estimated breakdown voltage using Lao's equations, as explained by Blair (1978); I calculated a voltage of ~3.4 x10^5v which, for a gap of 0.1m, translates into a maximum electric field of 3.4 x10^6.

$$V_{MAX} \approx 9.14\ ms^{-1}$$

This result demonstrates that, assuming 100% efficiency and a field strength at the point of electric breakdown (arcing), the maximum velocity of an ionic wind is 9.14ms-1. The breakdown voltage of air could be as low as 6.6kV in the right conditions (Blair, 1978), further lowering the maximum wind speed. Whilst a stationary object can only achieve an ionic wind speed of 9.14ms-1, it is important to consider the mechanism behind the ionic wind to understand whether this is the maximum speed of an EAD aircraft.

The ions moving between electrodes actually travel significantly faster than this value, it is only the atoms the ions collide with that will move, on average, at 9.14ms-1. The 9.14ms-1 limit describes the maximum relative flow velocity generated by the aircraft, but for a moving aircraft this could mean a much greater total velocity. Therefore, it is reasonable to state that an EAD aircraft could accelerate to speeds greater than 9.14ms-1; Barrett (2019) even claims that it could be possible to achieve supersonic flight with an ion-powered aircraft.

9.14ms-1 is too low a speed to lift a light aircraft although, taking into account the ion velocity, this is not a limit to the feasibility of ion-powered aircraft. This does explain the low force exhibited on the aircraft since the momentum of the moving air is relatively small. In comparison, the exhaust velocity of a turbofan engine can exceed 581ms-1 to propel heavier aircraft (Woodford, 2019). This means that ion propulsion cannot quickly accelerate an aircraft, but is still capable of reaching relatively high speeds.

Appendix C

Future Needs of Ion Thrusters

Clark (2019)

1. **"Dual mode thrusters that can meet orbit raising and station-keeping applications"**
This means thrusters which are capable of changing their thrust and I_{sp} throughout a mission. A single thruster could be used for all stages of the mission; this is a more versatile system than other ion thrusters and would help to save weight and costs.
2. **"Low cost, high volume market"**
Ion thrusters are of value to companies manufacturing 'mega-constellations' of satellites. They could reduce the cumulative cost of fuel and launch, where a small change in the weight of each satellite can significantly increase the cost of launch. However, for such large constellations, a low cost, high-volume manufacturing method must be achieved; this is very different from the conventional, bespoke manufacture of other ion propulsion systems.
3. **"Alternative manufacturing"**
Use of '3D Printing' would potentially be a step towards low-cost, high volume manufacture discussed above. Using 'selective laser sintering' to create metal components would reduce manufacturing costs. It is important that 3D printed parts can be verified to be equally as strong and resilient as the components they will be replacing.
4. **"Much longer life, looking at alternative materials and alternative propellants"**
Ion thrusters use fuel more efficiently than chemical thrusters, and so their fuel supplies will last longer. However, the thrusters themselves are at risk of degradation from sputtering and the high heat they are subjected to when in use. Ion engines must be made from durable materials, and future development in the heat resistance and durability of these materials can help to make them last longer in space. Additionally, it may be possible to explore optimising propellant composition. Whilst xenon fuel is useful (Appendix A.1), future developments could continue to optimise fuel in order to maximise the efficiency of the thruster.
5. **"High power, high thrust engines (10-50KW)"**
This is a major issue for ion thrusters. In order to combat their low thrust, development of solar technology or other power sources will need to be developed. For example, nuclear power can be used by satellites, although development is needed to find the most efficient and powerful solution.
6. **"Low thrust applications for smaller satellites working in a constellation"**
Low cost, low thrust engines could be used on smaller satellites in constellations, to perform the same task as a larger satellite. By using multiple, smaller satellites, it is easier for continuous operation to take place. This is because, in the event of a failure, only one smaller satellite needs to be replaced. This reduces maintenance and operational costs, as well as downtime after a failure.

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