Harvesting Near Earth Asteroid Resources Using Solar Sail Technology

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Near Earth asteroids represent a wealth of material resources to support future space ventures. These resources include water from C-type asteroids for crew logistic support; liquid propellants electrolytically cracked from water to fuel crewed vehicles and commercial platforms; and metals from M-type asteroids to support in-situ manufacturing. In this paper the role of solar sail technology will be investigated to support the future harvesting of near Earth asteroid resources. This will include surveying candidate asteroids though in-situ sensing, efficiently processing asteroid material resources and returning such resources to near-Earth space. While solar sailing can be used directly as a low cost means of transportation to and from near Earth asteroids, solar sail technology itself offers a number of dual-use applications. For example, solar sails can in principle be used as solar concentrators to sublimate material. If a metal-rich M-type asteroid is processed through solar heating, then the flow of metal resources made available could be manufactured into further reflective area. The additional thermal power generated would then accelerate the manufacturing process. Such a strategy could enable rapid in-situ processing of asteroid resources with exponential scaling laws. It is proposed that solar sailing therefore represents a key technology for harvesting near Earth asteroids, using sunlight both as heat for asteroid processing and radiation pressure for resource transportation.

Key Words: Solar sail, solar radiation pressure, near Earth asteroid, space resources

Nomenclature

a	:	solar sail characteristic acceleration
A	:	total reflector area
E	:	enthalpy of sublimation
F	:	solar flux at 1 AU
m	:	mass of reflector
M	:	mass of asteroid
r	:	radius of reflector
R	:	radius of asteroid
η	:	total reflective efficiency
κ	:	solar sail payload mass fraction
ρ	:	asteroid bulk density
σ	:	reflector areal density
τ	:	characteristic timescale

Subscripts

P	:	payload
T	:	total

1. Introduction

Accessing near Earth asteroid resources offers to transform both government space exploration and commercial space development. For example, water extracted from near Earth asteroids for crew logistic support could significantly reduce the cost of future human space ventures [1], avoiding the expense of lifting water out of the Earth's deep gravity. In the near-term water could also be used for propellant production through the electrolytic cracking of water resources into hydrogen and oxygen using abundant solar energy. Such in-situ propellant production could then supply crewed vehicles in Earth orbit or at the Lagrange points, or a range of commercial space platforms. Later, significant resources of platinum group and 'rare earth' metals could in principle be accessed to support future in-orbit manufacturing, and potentially to supply key terrestrial industries for the 21st century [2].

Renewed interest in asteroids has arisen partly since it is now understood that, as early solar system remnants, they provide important insights into the formation of the solar system itself. This has led to a number of science missions to target asteroids with many more missions planned [3]. A growing body of relevant research on asteroid science is therefore available. This includes an understanding of asteroid orbit evolution, their physical and mechanical properties and the design of highly-perturbed spacecraft orbits in the vicinity of asteroids [4,5].

Moreover, the impact hazard posed by near Earth asteroids has led to a growing body of work on strategies to manipulate asteroid orbits for risk mitigation [6]. The development of new concepts for orbit manipulation is clearly linked to future technologies for asteroid capture. Moreover, recent commercial interest in near Earth asteroids builds on prior work which has mapped out the potential scale of resources available and strategies for their utilisation [7]. Other on-going work covers a broad range of relevant research on asteroid surveys [8], technologies for water extraction [9], regulating access to near Earth asteroids [10], mission design for commercial resource extraction [11] and near Earth asteroid capture strategies [12].

A range of low-energy capture strategies have been developed which can leverage the natural gravitational interactions in the Sun-Earth system to enable capture using a minimum of engineering intervention. For example, the stable manifolds of the Earth-Sun L_1 and L_2 points can be used for low-energy capture, leading to a list of so-called Easily Retrievable Objects (EROS) [13]. Chaos-assisted methods also appear promising

[14]. Here, an impulse or low thrust arc can transfer a suitable near Earth asteroid from a chaotic orbit to a regular periodic orbit on a KAM torus. In this way the target object can be trapped, remaining in the vicinity of the Earth even although the zero velocity surfaces at the Lagrange points are open.

In this paper solar sail technology will be investigated as a means of supporting in-situ surveys of candidate asteroids, processing asteroid resources using direct solar thermal heating and returning these resources to near-Earth space using solar radiation pressure. In particular, direct solar heating will be considered using a parabolic solar sail to process metal-rich M-type asteroids. Through such direct heating metal resources can be liberated which are then available to be manufactured into further reflector area. The growing reflector area can then deliver additional thermal power to enhance the production of metals. In principle, the resulting positive feedback process results in accelerated manufacturing, whereby an initial modest seed mass of infrastructure delivered to Earth escape could ultimately process most of an M-type asteroid.

This accelerated manufacturing process will be modelled through a time-delay differential equation, which captures process delays. It will be shown that due to process delays in converting liberated metals into reflective membrane, the reflector area, and hence total mass processed, increases as a polynomial rather than exponential function of time. Finally, speculation on the long-term prospects for solar sailing as a tool for near Earth asteroid resource harvesting will be provided.

2. Resource surveys

Given the open-ended nature of solar sail propulsion, solar sailing can be seen as an excellent option for survey missions to assay candidate near Earth asteroids, providing estimates of available resources. A single solar sail can in principle visit multiple targets to provide cost effective surveys. Moreover, low cost CubeSat-scale solar sails using miniaturized instruments are now under development, such as the NASA NEA Scout mission with an 86 m^2 sail (Fig. 1) [15].

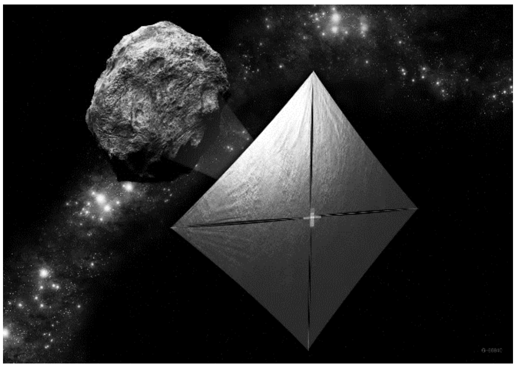

Fig. 1. CubeSat-scale solar sails for surveying multiple candidate near Earth asteroid targets (NEA Scout 6U CubeSat mission, NASA).

Given the relatively low mass and cost of such spacecraft, multiple solar sails can be envisaged to survey candidate targets in parallel, with a swarm of devices deployed from a single launch to Earth escape. Moreover, given advances in on-board autonomy, such 'autonomous explorers' could provide a network of mobile sensors, moving from target to target and thus providing a continuous flow of information on candidate near Earth asteroids over the long-term [16]. Such an expanding sphere of information on near Earth asteroid resources would be a precursor to follow-up resource harvesting activity.

Aside from using solar sails to transport survey instrumentation to target near Earth asteroids, in principle solar sails can also be used to assist with surveys after rendezvous. First, a solar sail can be stationed at an artificial equilibrium point on the illuminated side of a near Earth asteroid. This provides a unique vantage point for visual imaging as the asteroid rotates under the static solar sail [17]. Moreover, in principle sails could also be used as reflectors to illuminate shaded regions of near Earth asteroids from a suitable orbit or static equilibrium position. The NASA Lunar Flashlight mission will illuminate shaded lunar craters using a near infrared laser, although an earlier mission concept used a solar sail to provide direct illumination [18].

The effectiveness of surface illumination using a solar sail can be easily estimated. For a target near Earth asteroid at 1 astronomical unit (AU) the solar flux is 1378 W m^{-2}. For a flat sail with a reflective efficiency η of 0.85, pitched at an angle of 45^{o} to the Sun-line, the spot size can be estimated from the specular reflection of the image of the solar disk (angular diameter θ) onto the asteroid surface, as shown in Fig. 2. Given the angular diameter of the solar disk at 1 AU is 0.53^{o}, the spot size $d \cong h\theta$. The enhancement in illumination over direct solar illumination can then be estimated by determining the power intercepted by the solar sail, which is then reflected onto the surface spot [19]. Estimates of the illumination enhancement delivered are provided in Tables 1a and 1b for a range of sail altitudes h, although clearly non-specular reflection will reduce the illumination enhancement delivered by a realistic solar sail.

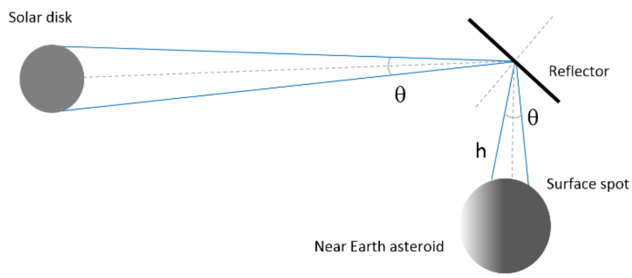

Fig. 2. Illumination of shaded regions on a near Earth asteroid by reflecting an image of the solar disk from a solar sail in orbit or static equilibrium.

Table 1a. Illumination enhancement from a 20 x 20 m solar sail at 1 AU.

Altitude *h* (km)	Spot size *d* (m)	Intensity enhancement (%)
5	47	14
10	93	4
25	233	0.6

Table 1b. Illumination enhancement from a 60 x 60 m solar sail at 1 AU.

Altitude *h* (km)	Spot size *d* (m)	Intensity enhancement (%)
5	47	127
10	93	32
25	233	5

3. Resource transportation

Again due to the open-ended nature of solar sail propulsion, solar sailing can be considered as an efficient means of round-trip transportation to return resources extracted from target near Earth asteroids. A number of extremely large (km-scale) solar sails can be envisaged to rendezvous with a set of target bodies, collect previously extracted resources and then return the resources to near-Earth space, for example to a suitable libration point in the Earth-Sun or Earth-Moon system. This cycling between near-Earth space and target near Earth asteroids would continue in an open-ended manner, limited only by the lifetime of the solar sail in the space environment.

A key question for such a transportation system is the optimum payload mass fraction for the solar sail. A low payload mass fraction will enable a short round-trip duration, but with a modest payload returned. A large payload mass fraction will deliver a significant payload, but with a long duration required for the round-trip. It is clear then that there will be an optimum payload mass fraction to maximise the average rate of return of resources [20].

The optimum payload mass fraction can be estimated assuming a quasi-circular spiral from near-Earth space to the target body, and then a slower return to near-Earth space with the resource payload. First, for a solar sail of area A and characteristic acceleration a_o (with resource payload), the total mass of the solar sail and payload is given by:

$$m_T = \frac{2\eta PA}{a_o} \tag{1}$$

where P is the solar radiation pressure at 1 AU and η is the sail reflective efficiency. Similarly, the payload mass transported by the solar sail can be written as [20]:

$$m_P = \left(\frac{2\eta PA}{a_o} - \sigma\right) A \tag{2}$$

where σ is the sail assembly loading, defined as the mass per unit area of the sail assembly without payload. The payload mass fraction of the solar sail $\kappa = m_P/m_T$ is therefore given by:

$$\kappa = 1 - \frac{a_o}{\tilde{a}_o} \tag{3}$$

where $\tilde{a}_o = 2\eta P/\sigma$ is the characteristic acceleration of the solar sail without payload.

It can be shown that for a quasi-circular heliocentric orbit, the trip time T between 1 AU and some arbitrary orbit radius scales approximately as the inverse of the solar sail characteristic acceleration, so that $T \cong \lambda/a_o$ for some constant λ [21]. The total round trip duration for a solar sail to spiral from near–Earth space to a target near Earth asteroid (without payload) and then return with a payload is therefore given by $T = \lambda/\tilde{a}_o + \lambda/a_o$. The average rate of return of resources is then defined by $J = m_P/T$ so that:

$$J = \frac{m_T}{\lambda}\frac{a_o\tilde{a}_o}{a_o+\tilde{a}_o}\left(1 - \frac{a_o}{\tilde{a}_o}\right) \tag{4}$$

In order to find the turning point of J it can be shown that $dJ/da_o = 0$ when $a_o = (\sqrt{2}-1)\tilde{a}_o$ and so the optimum payload mass fraction can be estimated as $\kappa \cong 0.6$. The turning point of J is shown schematically in Fig. 3.

For example, the NASA Space Launch System (SLS) Bock 1B has a payload capacity to C_3=0 of order 35 tonnes, allowing a large 1.9 x 1.9 km solar sail with an assembly loading of 10 g m^{-2} to be delivered to Earth escape. Assuming a sail reflective efficiency η of 0.85 the sail would then have a characteristic acceleration $\tilde{a}_o$ of 0.8 mm^{-2}. For a round-trip mission cycling to asteroid 1996FG$_3$ the outbound trip time is of order 200 days, with of order 600 days required for the return trip with the payload [21]. Since the optimum payload mass fraction is of order $\kappa \cong 0.6$ the sail would transport a 60 tonne payload, almost twice its own mass. The 800 day round-trip would then be repeated resulting in an average delivery rate m_P/T of order 27 tonnes of resources per year. A fleet of multiple solar sails would ensure a near continuous return of resources.

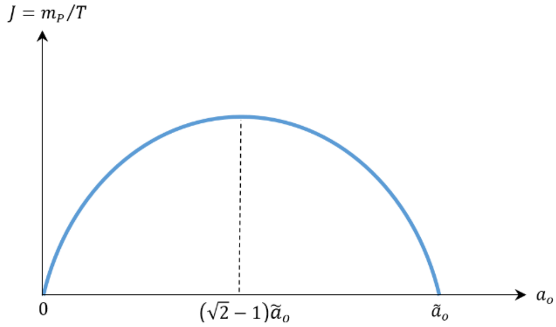

Fig. 3. Functional form of average rate of return of resources J as a function of the solar sail characteristic acceleration a_o.

4. Resource processing

4.1. Solar thermal heating using parabolic reflectors

In order to extract resources from a target near Earth asteroid a parabolic reflector can in principle by used to focus sunlight onto the asteroid surface, thus directly sublimating material which is then collected and processed. While sublimation by direct solar heating has been considered in some detail for asteroid deflection [22], a simple analysis is presented here to assess the scaling laws for resource extraction and processing.

To concentrate sunlight to directly sublimate material, a disk membrane reflector with a circumferential supporting hoop will be considered. The membrane reflectivity profile can be chosen such that solar radiation pressure deforms the slack membrane into a parabolic form, shown schematically in Fig. 4. Light pressure can therefore be used as a substitute for a mechanical structure to deliver the required profile. This strategy has been considered in some detail for both static and rotating disks [23].

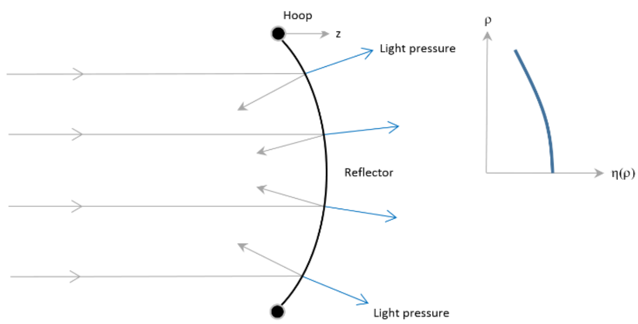

Fig. 4. Parabolic membrane reflector formed by solar radiation pressure acting on a membrane with a selected reflectivity profile.

By defining the required membrane shape to be a parabola, an inverse problem can then be solved to determine the required reflectivity profile. It will be assumed that the surface reflectivity is either engineered directly during manufacture using coatings or is actuated using active electrochromic elements. For a parabolic reflector of radius r the membrane displacement $z(\rho)$ at radius ρ can be defined such that:

$$z(\rho) = \tilde{z}\left(1 - \left(\frac{\rho}{r}\right)^2\right) \tag{5}$$

where $\tilde{z}$ is the membrane displacement at $\rho = 0$, while $z(r) = 0$ at the hoop edge and $z'(0) = 0$ at the disk centre. It can be shown that the required reflectivity profile $\eta(\rho)$ is given by [23]:

$$\eta(\rho) = \frac{1}{2}\sqrt{\frac{1 + \Lambda^2}{1 + \Lambda^2(\rho/r)^2}} \tag{6}$$

where $\Lambda = 2\tilde{z}/r$ and $\eta(r) = 1/2$ at the hoop, so that the membrane edge must be absorbing. A rotating disk allows ideal reflectivity $\eta(0) = 1$ at the centre and so is more efficient [23].

Since solar radiation pressure is used to generate the parabolic profile for the membrane, in principle the reflector will have a relatively low mass compared to a solid mirror. Moreover, even modest-sized membrane reflectors can deliver industrial-scale power. For example, an ideal 100 m radius parabolic reflector with a total areal density (including supporting structure) of 10 g m^{-2} can in principle develop of order 40 MW of thermal power at 1 AU. This represents an impressive power-to-mass ratio of order 140 kW kg^{-1}. Such a reflector could in principle enable in-situ manufacturing on industrial scales, leveraged from a seed mass of infrastructure launched from Earth.

For solar flux $F_{\odot}$ (1378 W m^{-2} at 1AU) the power generated by a reflector of area πr^2 and reflective efficiency η is simply $\eta F_{\odot}\pi r^2$. The mass flow rate of material liberated from the asteroid by direct solar heating is then of order:

$$\dot{m} = \frac{\eta F_{\odot}}{E}\pi r^2 \tag{7}$$

for an asteroid enthalpy of sublimation E. Assuming that the enthalpy of sublimation of an M-type asteroid is of order 6x10^6 J kg^{-1} (equivalent to Iron), then ignoring heat loss by radiation or condition into the asteroid, an ideal 100 m radius reflector will deliver a maximum mass flow rate $\dot{m}$ of order 6 kg s^{-1}. However, this upper limit does ignore the reduction in power collected due to the required membrane reflectivity profile.

4.2. Manufacturing with exponential scaling laws

For a metal-rich M-type asteroid the flow of material due to direct solar heating is in principle available to fabricate additional reflector area, for example by vapour deposition or additive layer manufacturing. The growing reflector area can then accelerate the sublimation of material in a positive feedback loop [24,25]. This assumes that additional processing capacity is itself manufactured to avoid resource bottlenecks.

It will now be assumed that the parabolic reflector is stationed in proximity to a target asteroid and delivers a flow of material through an ejecta plume, shown schematically in Fig. 5. Metals are assumed to be separated from the plume through capture at a cold plate and are then made continuously available for fabrication into additional reflector area.

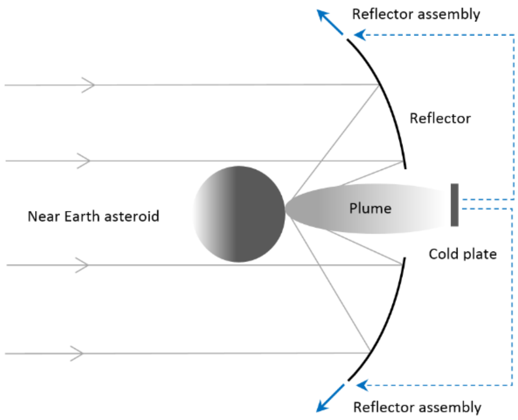

Fig. 5. Processing an M-type asteroid using direct solar thermal heating, with the metal flow used to enlarge the reflector area.

If it is now assumed that additional reflector area is being fabricated using the flow of metals from the asteroid, the instantaneous reflector area is simply $\pi r(t)^2$, where the area of the central cut-out is neglected for ease of illustration. If the reflector efficiency is again η, the power generated by the reflector is $\eta F_{\odot}\pi r(t)^2$, so that the instantaneous mass flow rate from the asteroid is now given by:

$$\dot{m}(t) = \frac{\eta F_{\odot}}{E}\pi r(t)^2 \tag{8}$$

Then, the instantaneous mass of the reflector with areal density σ is given by $m(t) = 4\pi\sigma r(t)^2$ so that:

$$\dot{m}(t) = 2\pi\sigma r(t)\dot{r}(t) \tag{9}$$

Assuming no losses from the flow of material, conservation of mass therefore requires that:

$$2\pi\sigma r(t)\dot{r}(t) = \frac{\eta F_{\odot}}{E}\pi r(t)^2 \tag{10}$$

which can be written as:

$$\dot{r}(t) = \frac{1}{\tau}r(t) \tag{11}$$

where a characteristic time constant $\tau = 2\sigma E/\eta F_{\odot}$ is now defined. The growth of the radius of the reflector $r(t)$ therefore follows an exponential scaling law with a characteristic time constant τ such that:

$$r(t) = r(0)\exp(t/\tau) \tag{12}$$

where $r(0)$ is the initial reflector radius, again neglecting the central cut-out for ease of illustration. For a reflector with an areal density of 10 g m^{-2} and again assuming an enthalpy of sublimation of order 6x10^6 J kg^{-1}, the characteristic time constant τ is of order 10^2 sec. This short time constant is largely due to the membrane nature of the reflector, where modest mass flows will deliver significant rates of growth of membrane area.

The change in the mass of the near Earth asteroid can then be obtained as the reflector area grows. If the instantaneous radius of the asteroid is $R(t)$ with bulk density ρ, its instantaneous mass is given by $M(t) = (4\pi/3)\rho R(t)^3$ so that:

$$\dot{M}(t) = 4\pi\rho R(t)^2\dot{R}(t) \tag{13}$$

Therefore, for a given mass loss rate due to direct solar heating, the rate of change of the asteroid radius is found from:

$$4\pi\rho R(t)^2\dot{R}(t) = -\frac{F_{\odot}}{E}\pi r(t)^2 \tag{14}$$

However, the instantaneous radius of the reflector is also known from Eq. (12) so that:

$$\int_{R(0)}^{R(t)} R'(t)^2 dR'(t) = -\frac{F_{\odot}\, r(0)^2}{4\rho E}\int_0^t \exp(2\,t'/\tau)dt' \tag{15}$$

where $R(0)$ is the initial radius of the asteroid. Integrating Eq. (15) the radius of the asteroid is therefore obtained as:

$$R(t) = R(0)\left(1 - \frac{3}{4}\frac{\sigma r(0)^2}{\rho R(0)^3}(\exp(2\,t/\tau) - 1)\right)^{1/3} \tag{16}$$

so that the asteroid radius decreases as mass is lost through sublimation. In the limit that $R(t) \to 0$ as $t \to t_f$ it is found that the time required to process the entire asteroid is given by:

$$t_f \cong \frac{1}{2}\tau \ln \Lambda \tag{17}$$

where $\Lambda = 4\rho R(0)^3/3\sigma r(0)^2$ is the ratio of the initial mass of the asteroid to the initial mass of the reflector. For a 100 m radius asteroid with a bulk density of 5.3 g cm^{-3} and an initial reflector area equivalent to a disk of 100 m radius with an areal density of 10 g m^{-2}, it is found that t_f is of order 10^3 sec. Again, this short timescale is largely due to the membrane nature of the reflector where modest mass flows will in principle deliver significant rates of growth of membrane area. However, by including process delays in fabricating new reflector area it will now be shown that the reflector will grow as a polynomial rather than exponential function of time.

4.3. Manufacturing with process delays

As material is extracted from the near Earth asteroid, clearly there will be a finite time required to process material flows and so manufacture additional reflector area. This processing time can be modelling using a delay differential equation. If there is a fixed process delay T then from Eq. (10) the growth of reflector area is now determined by:

$$2\pi\sigma r(t)\dot{r}(t) = \frac{\eta F_{\odot}}{E}\pi r(t-T)^2 \tag{18}$$

so that a delay differential equation is obtain such that:

$$\dot{r}(t) = \frac{1}{\tau}\frac{r(t-T)^2}{r(t)} \tag{19}$$

In order to solve the delay differential equation initial data is required, for example $r(t) = r(0)$ for $-T \le t \le 0$. Defining the unit of time to be the characteristic timescale τ, for a delay $T = \tau$ it can be shown using the method of steps that the delay differential equation has a solution for the non-dimensional reflector radius given by:

$$\frac{r(\tau)}{r(0)} = \begin{cases} 1 & \tau < 0 \\ \sqrt{1+2\tau} & 0 < \tau \le 1 \\ \sqrt{3 - 2\tau + 2\tau^2} & 1 < \tau \le 2 \\ \cdots & \cdots \end{cases} \tag{20}$$

so that the reflector area grows as a polynomial rather than exponential function of time. The solution to the delay differential equation defined by Eq. (20) is shown in Fig. 6 for a range of delays, including $\tau = 0$. Clearly, even for modest process delays, the rate of growth of the reflector area slows considerably. Moreover, relaxing the assumption that the entire mass flow from the asteroid is captured and processed into new reflector area will slow the maximum growth rate which can be achieved. The process delay will also increase as the reflector area grows due to the time required to transport material to the expanding edge of the reflector, while the reflector focal length will also need to slowly increase. However, this approximate analysis does indicate that closed-loop processing of a metal-rich asteroid into new reflector area can in principle be an effective means of accelerating the extraction of resources.

It can be envisaged that the new reflector area manufactured from the asteroid can ultimately be used to assemble solar sails to transport resources to near-Earth space. In this manner, the initial seed mass of infrastructure which initiates the processing of the asteroid is significantly leveraged, in principle by a factor of Λ. For the 100 m M-type asteroid and 100 m reflector discussed earlier this ratio is of order 10^8.

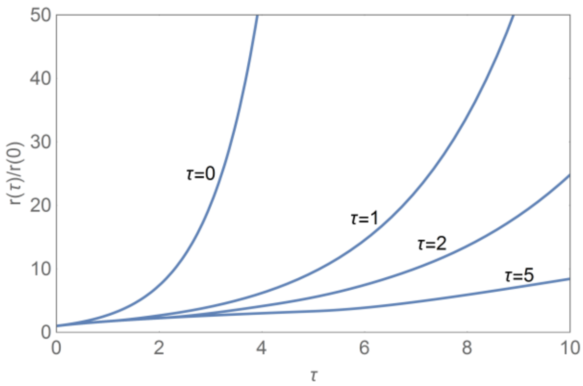

Fig. 6. Growth of reflector radius, with exponential growth for time constant $\tau = 0$ and slower polynomial growth for $\tau > 0$.

5. Long-term prospects

Although clearly speculative, a long-term strategy can now be envisaged. First, a solar sail is delivered to Earth escape and uses light pressure to reach a target M-type near Earth asteroid. The sail then uses direct solar thermal heating to process the metal-rich asteroids and fabricate additional reflector area, first to accelerate resource extraction and then to manufacture new solar sails. In this manner, an entire M-type asteroid can be processed and its resources returned to near Earth space, principally using solar thermal heating for manufacturing and solar radiation pressure for transportation. Moreover, the reflectors manufactured could use light pressure to reach other asteroids, and solar thermal power to process them, in a von Neumann-type self-replicating architecture.

By processing asteroids from bulk solids into thin membranes using solar thermal power, in principle relatively modest engineering interventions can be used to leverage significant outcomes. The interventions required need only engineer the geometry of a metal-rich asteroid from a sphere to a thin plate.

Finally, as noted in Section 3, through the use of membrane reflectors industrial-scale power can be delivered with an impressive power-to-mass ratio. Again this is due to the need only for a thin reflective surface to intercept and direct solar energy. Indeed, the energy intercepted by a membrane reflector quickly grows above that required for its manufacture [26]. This indicates that solar sails and reflective membranes offer to be important tools for industrial-scale space development, both for asteroid material processing and for resource transportation.

6. Conclusion

The application of modern solar sail technology to surveying, processing and transporting near Earth asteroid resources has been discussed. It is clear that solar sailing can offer significant benefits for harvesting asteroid resources, from transportation using solar radiation pressure to processing and manufacturing using solar thermal heating. In particular, using a parabolic reflector to extract resources, which are then manufactured into additional reflector area, offers the possibility of fast and efficient resource processing.

In order to utilise solar sail technology for near Earth asteroid applications, the size of solar sail required ranges from small CubeSat-scale devices for survey missions to ultra-large kilometre-scale structures for resource transportation. While challenging, these new applications provide a set of both near-term and long-term goals for solar sailing and opportunities for solar sail technology to contribute to the discovery, harvesting and utilisation of near Earth asteroid resources.

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