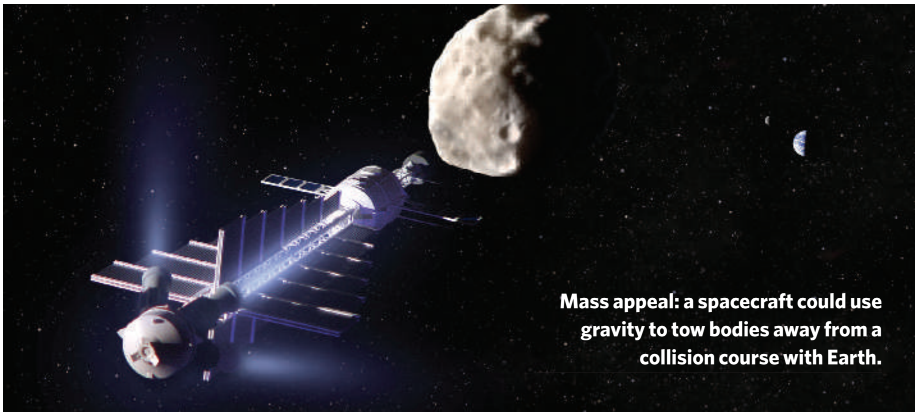
BRIEF COMMUNICATIONS

Gravitational tractor for towing asteroids

A spacecraft could deflect an Earth-bound asteroid without having to dock to its surface first.


Mass appeal: a spacecraft could use gravity to tow bodies away from a collision course with Earth.

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We present a design concept for a spacecraft that can controllably alter the trajectory of an Earth-threatening asteroid by using gravity as a towline. The spacecraft hovers near the asteroid, with its thrusters angled outwards so that the exhaust does not impinge on the surface. This proposed deflection method is insensitive to the structure, surface properties and rotation state of the asteroid.

The collision of a small asteroid of about 200 m with the Earth could cause widespread damage and loss of life[1]. One way to deflect an approaching asteroid is to dock a spacecraft to the surface and push on it directly[2]. The total impulse needed for rendezvous and deflection is too large for chemical rockets, but would be achievable by spacecraft such as the 20-tonne nuclear-electric propelled vehicles that were proposed as part of NASA's Prometheus programme[2].

Regardless of the propulsion scheme, a docked asteroid tug needs an attachment mechanism because the surface gravity is too weak to hold it in place. Asteroids are likely to be rough and unconsolidated, making stable attachment difficult. Furthermore, most asteroids rotate, so an engine anchored to the surface thrusts in a constantly changing direction. Stopping the asteroid's rotation, reorienting its spin axis[3], or firing the engine only when it rotates through a certain direction, adds complexity and wastes time and propellant.

Our suggested alternative is to have the spacecraft simply hover above the surface of the asteroid. The spacecraft tows it without physical attachment by using gravity as a towline. The thrusters must be canted outboard to keep them from blasting the surface (which would reduce the net towing force and stir up unwanted dust and ions).

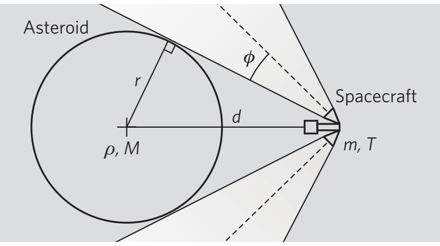

Figure 1 | Towing geometry of a gravitational tractor. The asteroid (assumed to be spherical) has radius r, density ρ and mass M. The spacecraft has mass m, total thrust T and an exhaust-plume half-width ϕ. It hovers at distance d from the asteroid's centre, where its net thrust balances its weight. The thrusters are tilted outwards to prevent exhaust impinging on the asteroid surface.

This scheme is insensitive to the poorly understood surface properties, internal structures and rotation states of asteroids. A spacecraft needs only to keep its position in the direction of towing while the target asteroid rotates beneath it. The engines must be actively throttled to control the vertical position as the equilibrium hover point is unstable. The horizontal position is controlled by differential throttling of engines on opposite sides of the spacecraft. The spacecraft can be made stable in attitude by designing it like a pendulum, with the heaviest components hanging closest to the asteroid and the engines farther away.

The thrust required to balance the gravitational attraction is given by

$$T\cos[\sin^{-1}(r/d)+\phi] = GMm/d^2$$
$$= 1.7\left(\frac{r}{d}\right)^3\left(\frac{\rho}{2\times10^3}\right)\left(\frac{m}{20\times10^3}\right)\left(\frac{d}{150}\right)$$

where G is the gravitational constant; see Fig. 1 for definition of other variables. Thus a 20-tonne spacecraft with $\phi = 20°$ hovering one half-radius above the surface ($d/r = 1.5$) can tow an asteroid of 200 m diameter and density $\rho = 2\times10^3$ kg m^{-3}, provided it can maintain a total thrust T of just over 1 newton.

The velocity change imparted to the asteroid per second of hovering (Δv) is given by

$$\Delta v = \frac{Gm}{d^2} = 5.9\times10^{-11}\left(\frac{m}{20\times10^3}\right)\left(\frac{150}{d}\right)^2$$

So the velocity change imparted to the asteroid in our example in a single year of hovering is 1.9×10^{-3} m s^{-1}. Because Δv is largely independent of the asteroid's detailed structure and composition, the effect on the asteroid's orbit is predictable and controllable, as would be required for a practical deflection scheme.

The mean change in velocity required to deflect an asteroid from an Earth impact trajectory is about $3.5\times10^{-2}/t$ m s^{-1}, where t is the lead time in years[4]. So a 20-tonne gravitational tractor hovering for one year can deflect a typical asteroid of about 200 m diameter given a lead time of roughly 20 years.

The thrust and total fuel requirements of our mission example would be well within the capability of proposed 100-kilowatt nuclear-electric propulsion systems[2], using about 4 tonnes of fuel to accomplish the typical 15 km s^{-1} rendezvous and about 400 kg for the actual deflection. For a given spacecraft mass, the fuel required for the deflection scales linearly with the asteroid mass.

Deflecting a larger asteroid would require a heavier spacecraft, more time spent hovering, or more lead time. However, in the special case in which an asteroid has a close Earth approach, followed by a later return and impact, the change in velocity needed to prevent the impact can be many orders of magnitude smaller if applied before the close approach[5]. For example, the asteroid 99942 Apophis (2004 MN4), a 320-m asteroid that will swing by the Earth at a distance of about 30,000 km in 2029, has a small probability (10^{-4}) of returning to strike the Earth in 2035 or 2036 (ref. 6). If it is indeed on a return impact trajectory, a deflection of only about 10^{-6} m s^{-1} a few years before the close approach in 2029 would prevent a later impact (A. Carusi, personal communication). In this case, a 1-tonne gravitational tractor with conventional chemical thrusters could accomplish this deflection mission as only 0.1 newtons of thrust would be required for a duration of about a month. Should such a deflection mission prove necessary, a gravitational tractor offers a viable method of controllably steering asteroid 99942 Apophis away from an Earth impact.

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GREEN CHEMISTRY

Biodiesel made with sugar catalyst

The production of diesel from vegetable oil calls for an efficient solid catalyst to make the process fully ecologically friendly. Here we describe the preparation of such a catalyst from common, inexpensive sugars. This high-performance catalyst, which consists of stable sulphonated amorphous carbon, is recyclable and its activity markedly exceeds that of other solid acid catalysts tested for 'biodiesel' production.

The esterification of higher fatty acids by liquid acid catalysts such as sulphuric acid (H_2SO_4) is a process commonly used for biodiesel production, but it involves high consumption of energy and the separation of the catalysts from the homogeneous reaction mixtures is costly and chemically wasteful. Recyclable solid acids, such as Nafion[1–4], make better catalysts, although they are also expensive and their activity is less than that of liquid acids[1]. Sulphonated naphthalene carbonized at 200–250 °C is a solid acid catalyst that has been used successfully for ethyl acetate formation[5]; however, it is a soft material and its aromatic molecules are leached out during liquid-phase reactions above 100 °C or when higher fatty acids are used as surfactants, so its catalytic activity is rapidly lost.

We have devised a strategy to overcome these problems by sulphonating incompletely carbonized natural organic material to prepare a more robust solid catalyst. Incomplete carbonization of natural products such as sugar, starch or cellulose results in a rigid carbon material that is composed of small polycyclic aromatic carbon sheets in a three-dimensional *sp*3-bonded structure. Sulphonation of this material would be expected to generate a stable solid with a high density of active sites, enabling a high-performance catalyst to be prepared cheaply from naturally occurring molecules.

The scheme we use to sulphonate incompletely carbonized saccharides is shown in Fig. 1. First, D-glucose and sucrose are incompletely carbonized at low temperature to induce pyrolysis and the formation of small polycyclic aromatic carbon rings; sulphonite groups ($-SO_3H$) are then introduced by sulphuric acid (see supplementary information). Structural analysis[6–8] indicates that the prepared samples consist of sheets of amorphous carbon bearing hydroxyl and carboxyl (–OH and –COOH) groups, as well as high densities of $-SO_3H$ groups.

This black powder is insoluble in water, methanol, benzene, hexane, *N,N*-dimethylformamide and oleic acid, even at boiling temperatures. It can be moulded into hard pellets or thin flexible films by heating with 0.5–5.0% by weight of binding polymer; the two forms have comparable stability and catalytic performance. The thin films act as electrically insulating proton conductors whose properties (0.09 siemens cm^{-1} at 50 °C and 100% humidity) are comparable to that of Nafion (0.1 siemens cm^{-1} at 80 °C).

High-grade biodiesel is produced by esterification of the vegetable-oil constituents oleic acid and stearic acid. The activity of our solid sulphonated carbon catalyst in this reaction is more than half that of a liquid sulphuric acid catalyst and much higher than can be achieved by conventional solid acid catalysts (see supplementary information). There was no loss of activity or leaching of $-SO_3H$ during the process, even for samples subjected to repeated reactions at 80–180 °C after having been recovered by simple decantation. The activity is double that of a carbonized sulphonated naphthalene catalyst tested previously[5], which decreased rapidly on recycling at 80 °C.

Carbon catalysts identical to those described here have also been successfully produced from carbonized starch and cellulose (results not shown). Saccharide molecules may therefore be generally suitable for preparing these catalysts, which can be used as a replacement for liquid sulphuric acid in esterification reactions. In addition to biodiesel production, such environmentally benign alternative catalysts should find application in a wide range of other acid-catalysed reactions.

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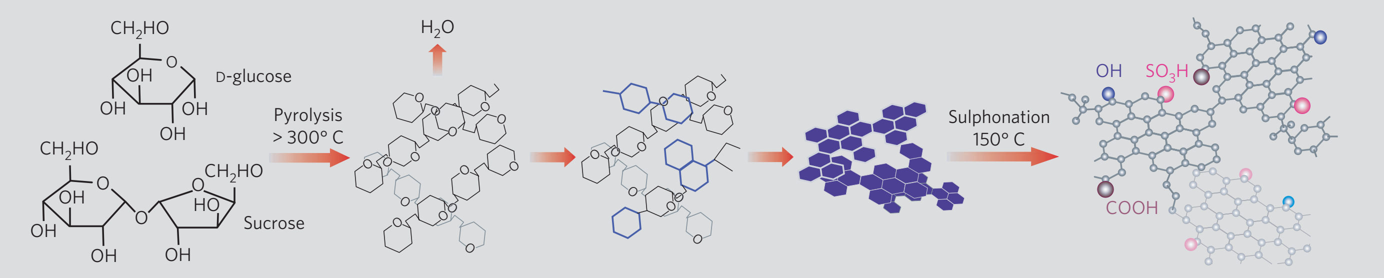

Figure 1 | Preparation from sucrose and D-glucose of a solid catalyst suitable for biological diesel production. Pyrolysis of the sugars causes their incomplete carbonization (middle; outlined in blue) and formation into polycyclic aromatic carbon sheets; sulphuric acid (concentrated or fuming) is used to sulphonate the aromatic rings to produce the catalyst. For details of methods, see supplementary information.