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ASTROENGINEERING, OR HOW TO SAVE THE EARTH IN ONLY ONE BILLION YEARS

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RESUMEN

Korycansky et al. (2001) presentaron un esquema con miras a alterar órbitas planetarias en el sistema solar, en particular aquella de la Tierra en un intento de escapar (durante un período) las consecuencias del abrillantamiento secular del Sol durante los siguientes miles de millones de años. En este artículo discuto este trabajo, presento información precedente y trato de entender las consecuencias de las ideas involucradas.

ABSTRACT

Korycansky et al. (2001) have presented a scheme for altering planetary orbits in the solar system, in particular that of the Earth as a means to escape (for a period) the consequences of the secular brightening of the Sun over the next few billion years. In this paper I discuss that work, present background information, and attempt to understand consequences of the ideas involved.

Key Words: **CELESTIAL MECHANICS — SOLAR SYSTEM: GENERAL — STELLAR DYNAMICS**

1. INTRODUCTION

Korycansky et al. (2001) have presented a scheme for altering planetary orbits in the solar system by means of targeted gravitational encounters among various solar system objects. In particular, we described an attention-grabbing application: moving the Earth to a larger orbit over billions of years, so as to counteract the effects of the Sun's gradual brightening as hydrogen is converted to helium in the Sun's core. In the present paper, I describe our work, focusing primarily on the background and other implications of the entire subject.

2. HOW TO MOVE THE EARTH

In this section I give a summary of the scheme. More details can be found in Korycansky et al. (2001). The basic idea makes use of energy transfers that occur in close encounters of two bodies in orbit around the Sun. This energy transfer mechanism has been in use now for several decades in planetary-probe missions, such as the Cassini mission now en route to Saturn.

To a good approximation, we can treat the passage in the planet's frame as a hyperbolic two-body encounter. In such an encounter, the small body's exit velocity has the same magnitude as the one with which it entered; only the direction has changed. In the frame centered on the Sun, the post-encounter velocity now has a different magnitude than did the pre-encounter one, so that there has been an energy transfer ΔQ per unit mass of the small body of

$$\Delta Q = (1/2)[(\mathbf{V}\cdot\mathbf{V})_{post} - (\mathbf{V}\cdot\mathbf{V})_{pre}]\,. \qquad (1)$$

The energy transfer turns out to equal the product of the circular orbital speed about the planet at the radius of closest approach, and the difference in tangential orbital speed (relative to the planet's orbit) post- and pre- encounter: $\Delta Q = V_c(V^T_{post} - V^T_{pre})$. Depending on the geometry of the encounter, ΔQ can be positive (as is usually the case with interplanetary probes) or negative (as in our scheme). In the latter case, energy is transferred from the smaller body to the planet, thus increasing its orbital energy and semi-major axis.

In our paper, we envisioned using Kuiper Belt Objects (KBOs) as the smaller body; given an estimate of a typical KBO mass, about 10^6 encounters are required to shift the Earth's orbit to that of Mars (1.5 AU). The process takes place over $\sim 6\times10^9$ years, leading to an encounter once every 6000 years or so on the average. The energy transfer per encounter would be $\sim 10^{34}$ erg.

We chose a basic orbit for the KBO of a period of $\sim$ 6000 years, or $\sim$ 325 AU. Initial encounter orbits are thus highly eccentric. It became apparent after working out the geometry that the post-encounter KBO orbits would still have aphelia beyond the radius of Jupiter's orbit. This led to the idea of including encounters with Jupiter to regain the energy lost to Earth by the KBO, so that one might in principle "recycle" the KBO with minimal energy require-

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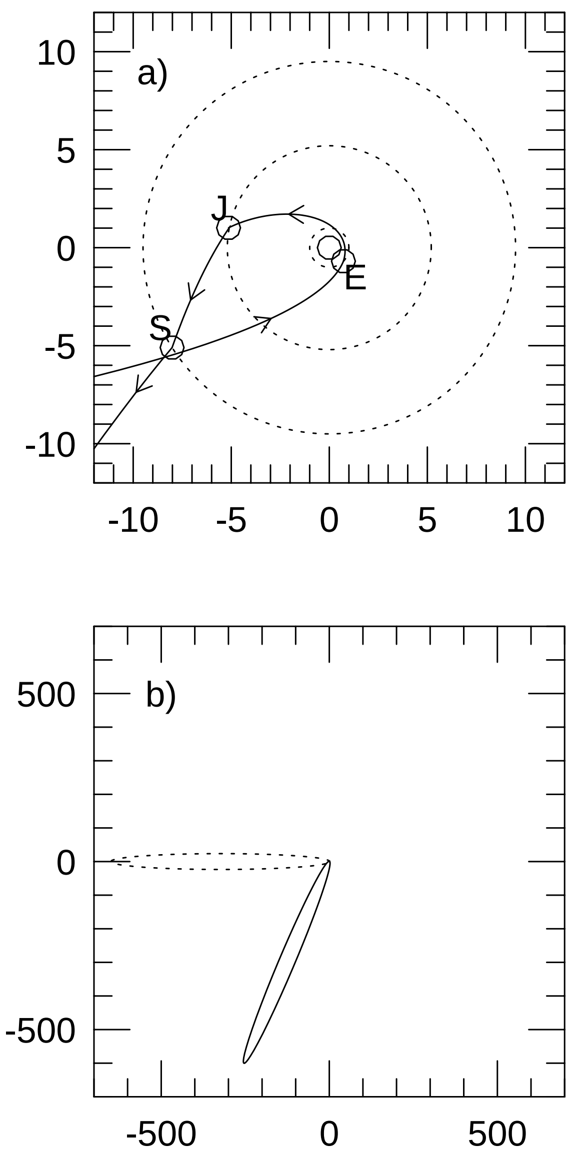

Fig. 1. Layout of successive encounters for an Earth-Jupiter-Saturn scheme, for an orbit with initial aphelion at 650 AU and aphelion tangential velocity 6000 cm s^{-1}. Note changes of scale from frame to frame; horizontal and vertical scales are in AU. a) Inner portion of successive orbits b) Initial (dotted) and return (solid) orbits compared.

ments. We found, however, that the new KBO orbit has a larger angular momentum than the initial orbit, requiring (if desired) more energy input to regain the initial configuration. This problem could be fixed by including additional encounters with a third planet, such as Saturn. Figure 1 shows how the KBO could encounter the Earth, Jupiter, and Saturn in turn. J. McCarthy (private communication) has pointed out to us that restoring the original KBO orbit (modulo orientation) requires the adjustment of two parameters, namely energy and angular momentum, and so two post-Earth encounters are required. The timing of multiple encounters is delicate, but not an insuperable obstacle (Korycansky et al. 2001).

The idea of advanced civilizations moving planets and engaging in other astroengineering projects has certainly been discussed elsewhere, partly in fiction (Stapledon 1937; Niven 1976; Oberg 1981; Taube 1982; Birch 1993a,b; Beech 1993; Fogg 2002; McInnes 2002). Other schemes for moving planets are no doubt possible, some of which may avoid some of the problems connected with our scheme that are discussed below. One idea is to introduce an artificial accretion disk of gas or dust near to the object that is desired to move. The object (i.e. the Earth) would induce spiral density waves in the disk. If the waves damp out in the disk (due to some sort of viscosity, such as turbulence), then there would be a transfer of angular momentum to or from the disk (depending on the relative orbital frequencies of the object and the disk). For example, a disk between the Earth and Venus would tend to push the Earth outward (and Venus inward). The timescale τ for orbital evolution due to torques in a gaseous disk scales like

$$\tau \sim \frac{1}{\Gamma}\left(\frac{c}{r\Omega}\right)^2 \left(\frac{M_\odot}{r^2\Sigma\Omega}\right)\left(\frac{M_\odot}{M_\oplus}\right), \qquad (2)$$

(Korycansky & Pollack 1993), where Γ is the dimensionless torque (of order unity) due to density waves driven in the disk, c is the sound speed in the disk, r is the orbital radius of the planet, $\Omega = (GM_\odot/r^3)^{1/2}$ the orbital frequency, and Σ is the disk surface density. Plugging in numbers for the Earth, and assuming a temperature of 300K at 1 AU in a disk composed of hydrogen, and a timescale of $\tau = 10^9$ years, the resulting surface density $\Sigma \sim 0.5$ gm cm^{-2}, quite a reasonable value by astronomical standards. However, the resulting total mass between ~ 1 and ~ 0.75 AU (the orbits of the Earth and Venus) turns out to be $\sim 1.5 \times 10^{26}$ gm or about 2.5% the total mass of the Earth; constructing such a disk would require the mobilization of mass on planetary scales.

3. CAVEATS

The original scheme as discussed in the paper has numerous problems and uncertainties, as we were well aware. Any one of them might render the original planet-moving scheme infeasible.

The most obvious potential hazard is that of impact. The scheme calls for numerous (a million!)

close flybys of the Earth by an object of order 100 km in size, passing at a distance of $\sim 10^4$km, at velocities of several tens of kilometers per second. Any single passage that went wrong would create a disaster of far greater magnitude than the Cretaceous-Tertiary impact that is thought to have caused the mass extinction 65 million years ago. The impact of a 100 km body would be approximately a thousand times more energetic, and might indeed be capable of wiping out higher life on the Earth; such events have probably not taken place on the Earth since the close of the "late heavy bombardment" some 3.8 billion years ago. The awful consequences of such a disaster may alone render the gravity-assist scheme too risky to use. However, the scheme might still be useful for other bodies, as discussed below.

Yet another problem is the vast timescale associated with an Earth-moving scenario. The timescale is set by the need to keep pace with the slow brightening of the Sun as it evolves. Thus, billions of years are involved. This is undoubtedly the most fantastic part of the whole scheme. Our paper was deliberately limited to the consideration of ideas involving known, or at least foreseeable, physics and technology (e.g. gravity assists, hydrogen fusion). The surprising thing is that it is possible to think about such enormous projects as being feasible with techniques that exist now, or at least are physically plausible, and which do not unduly strain the imagination—except for the timescales. Periods of hundreds of millions to billions or years are literally geological. The average biological species persists for a few million years, in general, and even that is some hundreds of times longer than human history. The thought of a technological enterprise that takes place over a period a thousand times longer still is perplexing indeed.

Korycansky et al. (2001) provided an estimate of the total energy required to move the Earth from its present orbit to one at the approximate distance of Mars. That estimate ($\sim 10^{36}$ erg) was based on the assumption that orbital corrections of $\sim 10^4$ gm cm^{-1} per encounter would suffice, for a 10^{22} gm object engaged in 10^6 passages over the entire period. This compares with the $\sim 10^{40}$ of gravitational potential energy involved in the total orbit change. The "leverage" results from the device of applying all velocity changes to the object at aphelion where orbital velocities are small and small changes have large effects in the resulting paths in the inner solar system. (Indeed, as noted in the paper, first-order velocity requirements can in principle be reduced to nearly zero by the use of multi-planet encounters. This leads to the interesting possibility that some sort of "automatic" mechanism could be set up that would cycle the KBO among the planets involved quasi-periodically to transfer energy among them [cf. McCarthy (2001)]. It is worth asking if such an energy estimate is at all realistic (if such a word can be applied to this project). In our paper for the most part we neglected the effects of planetary orbital inclinations and eccentricities, which could probably require additional velocity corrections and hence raise the amount of energy required to carry out the scheme.

Another obvious problem concerns the stability of orbits in the solar system after alterations of the orbits of major bodies. Altering the Earth's orbit might require changes in the orbits of other planets to restore stability, or continued shepherding to keep them under control. It is easy to imagine the problem spiraling out of control, or at least leading to a heavily "managed" system, which might be more trouble that it would be worth.

Finally, questions arise as to the effects on the Earth and the Moon. What would happen to Earth itself during this process? Two obvious issues are tides and spin changes. Transient tides of ~ 10 times the present size of those raised by the Moon could occur during an encounter. Buildup of angular momentum changes would seriously alter the Earth's spin, although varying the geometry of the encounters could mitigate that particular problem. Likewise, the Moon could be affected; we expect that set of encounters would tend to unbind the Moon, leaving it behind in near-Earth space. There is also a non-zero risk of collision of the KBO with the Moon. Both these problems could be avoided with sufficiently careful planning, however.

4. OTHER APPLICATIONS

For any of the reasons given above, it is possible—likely, even—that no conceivable civilization could or would attempt to move the Earth (or its analogue in another solar system). It may be, however, that the gravity-assist mechanism could be used on a smaller scale. One obvious application is impact-hazard mitigation, i.e. using gravity assists to alter the orbit of near-Earth objects (NEOs), that might present an impact hazard to the Earth. A variety of ideas have been proposed for this eventuality [cf. Gehrels (1994)]. We find that the gravity-assist scheme is inefficient compared with other mitigation strategies such as kinetic impact or stand-off blasts, due to the mismatch between the kinetic energy of the encounter and the energy delivered to the target:

ΔQ is so small as to render the gravity-assist mechanism non-competitive with other schemes. Large-scale gravity assists might be useful in other contexts, such as delivery of volatile material (e.g. water or organics) from the outer solar system, where it is plentiful, to the inner solar system, for such endeavors as colonies or terraforming of inner-solar-system bodies (e.g. Venus or Mars).

Gravity-assist techniques may take their place as part of the engineering tools used by advanced civilization that needs or wishes to alter the naturally-occurring orbital configuration in its solar system. Such tools might be available to humanity in next thousand years or so, at least for the smaller projects discussed above. It is also conceivable that the effects of astroengineering could be detectable from outside a system in which it has occurred; now that extra-solar planetary systems are being discovered in increasing numbers (including several examples of multi-planet systems), perhaps the possibility should be kept in mind (Marcos & Marcos 2003). A relatively obvious signature might be, for instance, planets on orbits that are not stable over the lifetime of the system, suggesting that some mechanism is keeping them in place. Examples of such situations might be orbital arrangements of the type discussed by Nauenberg (2001) and Laughlin & Chambers (2002).

5. ETHICAL-PHILOSOPHICAL ISSUES

The scale of the projects considered here, and their possible consequences for life in the solar system, make it worthwhile to pause for a consideration of ethical and philosophical questions that may arise. It is worth considering, whether even to think about or plan projects of astronomical engineering is to participate in what (Hartmann 1986) calls a "jingoistic boondoggle—the expression of a crazed technological society that insists on carrying through whatever mad schemes have become technologically feasible." Certainly, astroengineering is an example of the kind of project that raises important questions of responsibility (Pollack & Sagan 1993). It may be instructive to compare this problem with ones that arise concerning terraforming of planets, that is, altering their climates to render them more Earth-like, for human habitability and the introduction of a biosphere like that on Earth. Ethical aspects of terraforming, especially of Mars, have been considered, for example, by some workers in the field (Haynes 1990; McKay 1990; McKay & Haynes 1990; McKay 2001). McKay (1990, 2001) discusses terraforming in the context of principles of contemporary environmentalism, which may be applicable to this problem.

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