A CASE STUDY OF A MISSION TO THE KORDYLEWSKI CLOUDS USING ION PROPULSION

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ABSTRACT

A proposed mission to send a spacecraft to one of the stable Earth-Moon Lagrange points is described. The main objectives of the mission are scientific - the investigation of the Kordylewski clouds. The positions of the L-points are shown in Fig. 1 and they may be divided between the stable (equilateral) points and the unstable (co-linear) points.

If, in the ideal problem, an infinitely small body were to be placed at any of the L-points, it would stay at that point relative to the two major bodies indefinitely assuming a correct initial velocity. The points L1, L2 and L3 are 'unstable' in that the equations of motion of a small body within a small vicinity of these points indicate that a steady drift away from the point will occur. However, the equivalent equations for the 'stable' L-points show that no such drift will occur and the particle will be maintained within the vicinity of the Lagrange point. In reality, such as in the case of the Earth-Moon system, external forces including solar gravitation and the solar wind will alter the equations of motion. Nevertheless, it is found that stable periodic orbits around the libration points are still possible.

For a considerable period the Lagrange solutions found no practical application in astronomy. However, starting in 1904 Achillells and other 'Trojan' asteroids were discovered and found to be located at the stable L-points of the Sun-Jupiter system. Since then bodies have been found at the L-points of planet-moon systems such as Saturn and its moons Tethys and Dione. Study of the Earth-Moon Lagrange points was initiated by Khepmerrer and Benedict, who argued that, by analogy, the Trojan asteroids would be a collection of fine cosmic bodies might be found at these places.

In 1961 K Kordylewski of the Krakow Observatory, Poland, reported dim glows emanating from the region surrounding the Earth-Moon L4 and L5 points. These 'Kordylewski clouds' had the appearance of faint tenuous clouds shifting against the celestial sphere with the same motion as the Moon. Subsequently, Simpson backed up Kordylewski's observations but only after more than two years of searching. Several NASA high-altitude flights dedicated to visual observation of these phenomena by impartial observers again produced positive results. Even so, some controversy over the existence of these Libration-point clouds persisted, fuelled perhaps by the lack of a distinct photograph. Furthermore, ground-based observation of such tenuous objects are very hard to repeat reliably due to atmospheric distortions, reflected moonlight and interference from the Milky Way and the Zodiacal light.

To overcome the significant difficulties of ground-based observations, satellite-borne telescopes have been used. The Orbiting Solar Observatory OSO-6 'Zodiacal Light Analyser Experiment' covered a 15 month period in 1969/70 and produced some distinct and positive results from the Kordylewski clouds concluding that they were approximately 6" in angular size as seen from the Earth and moved around the Lagrange point over an elliptical zone with a semi-major axis of about 6" along the ecliptic and a semi-minor axis of about 2" perpendicular to the ecliptic. The absence of atmospheric scattering during these observations makes them particularly valuable. Experiments to determine forward scattering of light from the Kordylewski clouds were carried out on Skylab.

This paper reports the views of the authors and not those of the Royal Aerospace Establishment.
again indicating that a dust concentration appeared to exist in the region of the L4 and L5 points. An interesting ground-based telescopic investigation of the Earth-Moon L-points has been carried out by Fuentes and Valdes to determine whether any discrete objects exist at these places (their interest lay in the possible use of L-points as convenient parking places for ancient extra-terrestrial spacecraft). Their search indicated that no object having a diameter of Skylab or larger is positioned at the stable Earth-Moon L-points (assuming a reflectivity equal or greater than that of the Moon). However, smaller discrete objects are not ruled out.

The nature and origin of any material existing at the Earth-Moon Lagrange points is a matter of some interest. Much of the dust detected by normal satellite impact detectors is of cometary or asteroidal origin. Such material is normally in heliocentric orbits with velocities of 10-30 km\(^{-}\)s\(^{\circ}\) relative to the Earth, unless it is slowed by the Earth's atmosphere. These large velocities mean that such material is unlikely to have collected at the Lagrange points. However, meteoric erosion of the Moon is a continual process. It has been estimated\(^{18}\) that up to 10 tons of material falls upon the Moon each day but an even greater quantity leaves the surface, 15% of which passes into the Moon’s orbit. This material could be dust or larger discrete objects. The complex history of the Moon is not well understood and recent work to account for the wandering of the Moon’s spin axis\(^{9}\) has concluded that the Moon originally had a number of satellites of its own which broke up under tidal action. It would appear therefore that a more likely origin of material at the Earth-Moon Lagrange points is from the Moon itself, or the bodies which have collided with it.

3 FEATURES OF THE PROPOSED MISSION

The purpose of this paper is to describe the main features of a mission to send a spacecraft from the Earth to the Earth-Moon Lagrange points. The main purpose of the mission would be to gather evidence about solid material which exists in Earth-Moon space and, in particular, about the material in the region of L4 and/or L5. Such a spacecraft could return valuable information about the history of the Earth-Moon system. It is proposed that the spacecraft is launched into a circular Earth-orbit in a plane approximately that of the Moon’s orbit. Xenon ion thrusters would then be used to gradually raise the orbit altitude in a spiral motion which would continue for a long period (perhaps years). During this period a mapping of Earth-Moon space would be performed enabling any concentrations of dust to be located. The orbit-raising continues until lunar altitudes (378,000 km) are reached, and then a number of carefully timed manoeuvres are carried out to ensure rendezvous with one of the stable Lagrange points. The use of ion propulsion enables the journey from low-Earth orbit to lunar altitudes to be completed with a remarkably modest 30-40 kg of propellant for a 150 kg spacecraft. This has already been pointed out by Knock et al.\(^{10}\) of the Jet Propulsion Laboratory.

The instrumentations on the spacecraft would include a sensitive CCD camera and/or telescope which might be able to resolve discrete bodies which are too small to be seen from the Earth. A polarimeter should be carried to study the polarisation of scattered and reflected light from dust concentrations and this property could be studied from a variety of aspects and lighting conditions. Clearly dust detectors would be carried, but some of these would have to be of a new design capable of detecting dust which has only a small relative velocity compared to the spacecraft. Radio beacons can be used to track the motion of the spacecraft in the vicinity of the Lagrange point so providing information on disturbing forces and likely trajectories of the particles which form the Kordylewski clouds.

There are several other good reasons for performing such a mission, related either to scientific interest or to potential applications of L-points. The Earth-Moon Lagrange points have been suggested as suitable locations for space stations\(^{11}\) or, more immediately, as possible positions for communications satellite transmitting antennas. It is therefore proposed to investigate the stability of the L-points for practical purposes. The stable Lagrange points are located outside the immediate geomagnetic field of the Earth and could therefore prove advantageous as positions for performing long-term solar flare observations. For astronomical purposes the Lagrange points offer the opportunity of a nearly complete continuous view of the celestial sphere compared with the restricted view from Earth satellites.

4 APPLICATION OF ION PROPULSION

Ion propulsion offers a number of important advantages to a scientific mission of this type, not least in reducing the cost of the initial launch. In practice a mixture of electric and chemical primary propulsion may be desirable to reduce overall journey times, but since the journey could itself prove to be a valuable part of the mission the use of ion thrusters alone for the primary propulsion is proposed here. The principal advantages of using ion propulsion are identified below:

4.1 Propellant Requirements

The AV requirement for the proposed mission is very close to that for escape from the Earth-Moon system, ie about 4 km\(^{-}\)s\(^{\circ}\) from a 1000 km circular orbit. Currently available ion thrusters (with specific impulses in the mid-3000 seconds range), could, on a 300 kg spacecraft, produce an AV of this magnitude for as little as 50 kg of propellant. Using a solid motor, however, 75% of the spacecraft mass would have to be devoted to primary propulsion leaving only a very small payload. The use of ion propulsion implies that relatively low-cost launches can be utilised, possibly by sharing with other payloads going into low-Earth orbit.

4.2 Rendezvous with L-points

The difference between the AV required to reach the L-points and that required to escape from the Earth-Moon system\(^{12}\) is a mere 10 ms\(^{-}\)s\(^{\circ}\) which represents 0.25% of the total 4 km\(^{-}\)s\(^{\circ}\) AV required to achieve rendezvous with the L-points, instead of escaping, or being caught by the Moon, is therefore a very sensitive manoeuvre. Rendezvous could be attempted by the Hohmann transfer technique but there is uncertainty in the actual thrust and burn times obtained from the usual solid motors which, together with uncertainties in initial velocity, make the use of this method alone rather hazardous.\(^{14}\) Also, since these manoeuvres are 'one-offs' there is little room for mistakes. Continuous low thrusts available from ion propulsion systems would enable a carefully corrected trajectory to be followed so ensuring rendezvous given a reasonable set of initial conditions.\(^{14}\) Furthermore, once insertion into the correct orbit has been achieved the vehicle will be disturbed only by solar gravitation and the solar wind amongst other forces. Some initial analysis\(^{15}\) has shown that the necessary station keeping accelerations are within the range 2.3 x 10\(^{-}\)7 m\(^{-}\)s\(^{\circ}\) to 3.0 x 10\(^{-}\)7 m\(^{-}\)s\(^{\circ}\) which corresponds to a range of thrusts from 7 to 9 mN.
for a 300 kg spacecraft which is ideal for ion propulsion systems.

4.3 Spiral Orbit-raising

Spiral orbit-raising at low accelerations is a slow process which could be a severe disadvantage for some applications. However, on a scientific mission of this nature the incremental increases in altitude could prove valuable for obtaining a 'map' of certain parameters such as dust distributions or plasma conditions. The orbit-raising procedure which might last a number of years with continuous thrusts could in fact be temporarily stopped or even reversed if significant findings were made at a certain altitude. It should be noted, however, that if the orbit-raising commences from a low altitude below the Van-Allen belts (≈1000 km) then a considerable total dose of radiation can be expected which might cause solar array output to decline by up to 50%, depending on the technologies used.

5 SPACECRAFT DESIGN APPROACH

5.1 Ion Propulsion System

The baseline ion propulsion system proposed for the spacecraft is the UK-10 ion thruster currently under development to flight status by RAE. The UK-10 has been designed primarily for North-South station-keeping on communications satellites, however, it could be equally applicable to the 'interplanetary' mission described here.

Fig 2: The UK-10 Ion Thruster Schematic.

The UK-10 which uses Xenon as a propellant, has a 10 cm diameter grid system and can produce thrusts in the range 3-70 mN assuming sufficient power is available. In addition to the thruster, a Power Conditioning and Control System (PCCS), Propellant Flow Control System and Xenon storage tanks are necessary. Specifications of the UK-10 T4A thruster are shown below:

**T4A Ion Thruster Specifications**

- Propellant: Xenon
- Nominal thrust: 11.4 mN
- Demonstrated thrust range: 3-70 mN
- Exhaust velocity (singly charged ions): 37 km/s
- Specific impulse: 3790 (3171)
- Power-to-thrust ratio: 24.1 W/mN
- Mass Utilisation Efficiency: 89.8 (82.7)
- Thruster mass: 1.0 kg
- PCCS mass: 8.0 kg
- Cabling mass: 0.5 kg
- Flow Control mass: 4.3 kg

Note: Figures in brackets have been corrected for the presence of doubly-charged ions, neutraliser power and flow rate, and keeper discharge power. The Xenon propellant is stored under pressure. At a pressure of 60 bar the gas may be kept at its critical point and will have a density of 0.5 g/cc i.e half that of water.

5.2 Power System and Arrays

The use of ion propulsion immediately places significant requirements on the spacecraft's power generation system. For a 20 mN thrust about 700 W is required at the input to the PCCS. If continuous thrust is desired then a sun-pointing array is necessary. Gallium arsenide solar cells are proposed since, apart from their greater efficiency compared to silicon types, they are more resistant to radiation damage. The solar arrays will need to be oversized, perhaps by a factor of two, because of the consequences of radiation damage during
passage through the radiation belts. Thus the total solar array should be capable of generating in the region of 1.5 kW of power. For analysis purposes a constant 700 W of power was assumed to be available to the ion thruster, but in practice continuous throttling of the thrust level would be used to take full advantage of all available power at the various stages of the mission.

5.3 Spacecraft Configuration and Altitude Control

For maximum efficiency of the thrusting strategy, the solar array panels should be aligned normal to the spacecraft-Sun line and the thrust vector should be tangential to the orbital path. A further consideration is that antennae should be kept pointing towards the Earth – see Fig. 3.

![Fig. 3: Tangential Thrust Strategy](image)

The above requirements on the attitude of the spacecraft and solar arrays are analogous to those which apply to a geostationary satellite. It is therefore proposed that the spacecraft’s basic configuration can be based upon a scaled-down communications satellite – as shown in Fig. 4.

During an orbit, the body of the spacecraft rotates to keep the thrust vector tangential and the main antenna pointing to Earth.

Periodic momentum dumping will be required, as will some initial orientation manoeuvres after launch. Also manoeuvres will be necessary on approach to the Langrange-point for thrust-vector positioning and possibly for experimental reasons such as camera pointing. Therefore a number of hydrazine thrusters are suggested for attitude control. For station-keeping ion-propulsion would be used by suitably orientating the spacecraft to achieve the correct thrust vector. Station-keeping might be eased by placing ion thrusters on a number of selected faces of the vehicle so that complete spacecraft re-orientation is not required. This might be particularly useful for the North-South manoeuvres. The various thrusters would be operated from one or two centrally switched PCCS units to avoid duplication of the power electronics system.

6 INITIAL LAUNCH AND ORBIT RAISING

It is assumed that for cost reasons a launch to only a low altitude circular orbit is achieved initially. The plane of the orbit should be close to that of the Moon’s orbit in order to avoid large plane changes. However, the near-Earth orbit will be subject to precession in any case and the final adjustment of plane must take place later in the mission. There is a certain minimum altitude of launch because of atmospheric drag. Electric propulsion requires the deployment of solar arrays and the thrust produced increases with available power. However, drag also increases in proportion to array area and this implies a specific minimum launch altitude which depends upon such factors as power-to-thrust ratio and solar array efficiency.

This minimum altitude is calculated to lie in the region of 300 km for a solar maximum atmosphere which implies that a standard Shuttle launch would not be high enough at such times. 17.

Orbit raising to lunar altitudes, using ion propulsion, has been analysed using a numerical computer program 18 which takes into account the following points:

- a. thrust vector
- b. atmospheric drag (solar maximum)
- c. shadowing (no thrust in eclipse – this is significant at low altitude orbits)
- d. time of year
- e. major orbital perturbations due to asphericity of the Earth.

Using the numerical program, spiral orbit raising from 350 km to lunar altitudes has been analysed. A 300 kg start-of-mission spacecraft was assumed.
which can supply a constant 20 mN of thrust
tangential to the circular orbit. The resulting
time-altitude graph is shown in Fig. 5.

![Graph](image)

**Fig. 5: Orbit-raising from Earth to Moon**

To achieve a 378000 km altitude requires 60 kg of Xenon propellant after correction for the thruster mass utilisation efficiency and takes approximately 1200 days.

7 **REACHING THE LIBRATION POINT L₅**

7.1 **Coordinate System**

A computer model of spacecraft motion in an idealised Earth-Moon system has been employed to illustrate a strategy for reaching the L₅ libration point using a nominal 20 mN ion motor. The coordinate system is shown in Fig. 6.

![Diagram](image)

**Fig. 6: Earth-Moon coordinate system.**

When the spacecraft is situated at L₅ the Earth-Moon-spacecraft positions form an equilateral triangle with the vehicle trailing the Moon at the same tangential velocity of 1018 m/s.

The equations of spacecraft motion in two dimensions are:

\[
\begin{align*}
\dot{x} &= a_x - \frac{K(1 - u)(x - x_1)}{r_1^3} - \frac{Ku(x - x_2)}{r_2^3} \\
\dot{y} &= a_y - \frac{K(1 - u)(y - y_1)}{r_1^3} - \frac{Ku(y - y_2)}{r_2^3}
\end{align*}
\]

where

\[
\begin{align*}
r_1 &= \sqrt{(x - x_1)^2 + (y - y_1)^2} \\
r_2 &= \sqrt{(x - x_2)^2 + (y - y_2)^2} \\
x_1 &= D(1 - u) \cos(\omega t + B) \\
y_1 &= D(1 - u) \sin(\omega t + B) \\
x_2 &= D(1 - u) \cos(\omega t + B + \pi) \\
y_2 &= D(1 - u) \sin(\omega t + B + \pi)
\end{align*}
\]

7.2 **L₅ Rendezvous Strategy**

If the spacecraft maintained a specified tangential thrust from a suitable starting position, the spacecraft could be made to finally pass through the L₅
point on its spiral orbit. However, this simple approach would not enable the spacecraft to subsequently orbit the Earth at this location as the magnitude and direction of the arrival velocity would never be correct.

Using the computer program, it was demonstrated that if the spacecraft is briefly rotated by 90° to enable the ion motor to thrust radially, the angle and velocity could be accurately adjusted for subsequent orbiting at the L5 point.

The overall strategy involved determining the tangential thrust and radial thrust points with a chosen initial vehicle position approximately 90° ahead of the Moon on a 245 x 10^6 m orbit radius. A greater initial radius would be unadvisable as a vehicle–Moon conjunction could produce a subsequent Lunar impact or very near approach. This situation is illustrated in Fig. 7.

Adjust t2
Compute orbit until V_sc=0
Adjust t1
Adjust F_tang

Fig. 8: Rendezvous program flowchart.

Although the parameters are not independently variable, F-tang predominantly controls the final position. The final velocity magnitude and direction are adjusted by the duration and angular location of (t2-t1) respectively. The equations of motion are integrated using the Runge-Kutta-Merson method.

Fig. 9 illustrates the orbit path and final parameters.

The initial parameters chosen for the program at time t = 0 are:

Vehicle mass = 235 kg
Earth to spacecraft distance, R_se = 2.4497 x 10^8 m
Moon to spacecraft distance, R_sm = 4.3959 x 10^8 m
x = -1.5758 x 10^6 m
y = 2.4464 x 10^6 m
\dot{x} = 1.2622 x 10^6 m/s
\dot{y} = 65.5 m/s
Specific impulse = 3000 s

In addition, the radial thrust is initially 22 mN.

The solution involves evaluating the tangential thrust (F-tang) and the locations t1 and t2, during which the spacecraft is rotated 90° for an orbit adjustment. At the beginning of the program, an approximation is substituted for the three parameters F-tang, t1 and t2 and by iteration around the loops shown in Fig. 8, the final values are computed to the designed accuracy.

7.3 Computer Program

To summarise, the rendezvous orbit takes 37.2 days to complete and requires a 22 mN radial thrust at 28.6 days. This radial thrust adjustment is for a period of 51 hours. The steady tangential thrust computed is 22.57 mN. The ion motor consumes 2.5 kg of propellant over the whole rendezvous period.

7.4 Orbit Error Effects

Fig. 10 is a plot of the spacecraft's oscillatory
motion at a libration point over a 1.5 year period.

This component of the vehicle's motion is depicted by continuously rotating the coordinate system at the Moon's angular velocity. In this figure the spacecraft is placed at a libration point but given an initial tangential velocity of 1010 m/s (ie an error of -8 m/s). For clarity the resulting oscillation around the L-point is also shown magnified x 10 and translated to the coordinate position 0,0. A similar oscillation occurs for a 1° error in the initial velocity direction. To further investigate this motion the period was extended to 4.6 years showing the oscillations gradually increasing.

8 CONCLUSION

The collection of material at the stable Earth-Moon Lagrange points is a matter of serious scientific interest. Observations both from Earth-based telescopes and satellites have produced good, but not finally conclusive evidence of the existence of the Kordylewski clouds. A spacecraft mission to the Earth-Moon Lagrange points would be able to collect evidence not only about the material at these points, but also about the distribution of dust in Earth-Moon space.

Low-thrust ion propulsion systems (such as the UK-10) provide a suitable means of propelling the spacecraft from a near-Earth circular orbit to lunar altitudes. The resulting spiral motion would provide an opportunity to map a large area of Earth-Moon space. Ion propulsion also has the advantage of requiring only a very small mass of propellant (~60 kg for a 300 kg vehicle) which implies a large payload of science instruments. The rendezvous with the L-point and subsequent station keeping are also considerably eased by the use of electric propulsion instead of conventional chemical systems.

9 REFERENCES