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ACADEMY TRANSACTIONS NOTE

PLANETARY DEFENSE FROM THE NEAREST 4 LAGRANGIAN POINTS PLUS RFI-FREE RADIOASTRONOMY FROM THE FARSIDE OF THE MOON: A UNIFIED VISION

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Abstract—A unified system of five space bases is proposed to achieve both the Planetary Defense of the Earth against dangerous asteroids and the RFI-free Radioastronomy from the farside of the Moon.
We show that the layout of the Earth–Moon system with the five relevant Lagrangian points in space leads naturally to only one, unmistakable location of space bases within the sphere of influence of the Earth. This is:

(1) The two Lagrangian Points L1 (in between the Earth and the Moon) and L3 (in the direction opposite to the Moon from the Earth) are to be utilized mainly for the Planetary Defense. This means placing at L1 and L3 bases of missiles capable of deflecting the trajectory of dangerous asteroids and comets by hitting them *orthogonally* to their impact trajectory toward the Earth, so as to maximize their deflection. In this paper we show that *confocal* conics are the best class of trajectories fulfilling this orthogonality requirement.
(2) Out of all craters on the farside of the Moon, crater Daedalus (located just at the Earth's antipode at 180°E) is to be reserved for RFI-free radioastronomy. By RFI-radioastronomy we mean radioastronomy kept free from the flood of man-made radio frequency interference (RFI) that is shielded by the body of the Moon. In particular, we also mean SETI, the search for extraterrestrial intelligence. The Saha crater usage for this task was suggested by the French Radioastronomer Jean Heidmann back in 1994, but he untimely passed away on 3 July 2000. Currently, the IAA Cosmic Study on "Lunar SETI", started by Heidmann, is being coordinated by the author of this paper under the more general name of "Lunar Farside Radio Lab". Additionally, in this paper a new type of mission to the farside of the Moon is suggested for the first time: it is dubbed "RadioMoon" and intends to land a phased array for RFI-free radioastronomy and SETI inside crater Daedalus. The radio link and data downloading between the Earth and hidden crater Daedalus is envisaged to be done by a relay satellite orbiting the Moon in the equatorial plane.
(3) The Lagrangian point L1 can be used for all purposes (in addition to the Planetary Defense listed at 1) in as much as the body of the Moon shields the whole of the farside from the RFI produced at L1.
(4) The Lagrangian point L2 (beyond the Moon as seen from Earth) must be kept free from RFI-producing devices at all times in order not to damage the RFI-free environment on the farside of the Moon.
(5) The Lagrangian point L4 (preceding the Moon at 60° along its orbit around the Earth) can be used for all purposes, including all types of RFI-producing devices and possibly including a big space station of the Jerry O'Neill type (as shown in the "2001: An Odyssey in Space" movie). This is because the body of the Moon shields the farside from being reached by the RFI produced at L4. It could also be used for Planetary Defense.
(6) The Lagrangian point L5 (following the Moon at 60° along its orbit around the Earth) can be used for all purposes only in the plan of Moon farside activities put forward by the author in this paper (namely using crater Daedalus instead of Saha). However it could *not* be used in Jean Heidmann's plan because RFI-producing devices located at L5 would have polluted Saha directly. In this sense, the author's crater Daedalus proposal is an improvement over Heidmann's crater Saha proposal. © 2002 Published by Elsevier Science Ltd.

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1. INTRODUCTION TO BOTH PLANETARY DEFENSE AND RFI-FREE RADIOASTRONOMY

Since about 1980, two major needs for humankind that have emerged neatly:

(1) The need for the defense of the Earth against the fall of dangerous asteroids and comets on the Earth's surface, usually called "Planetary Defense". That fall could possibly cause severe casualties to humankind if not wipe many forms of life away, including humanity, as it happened already 65 million years ago with the dinosaurs and other species. Since the pioneering work of the late Nobel laureate Luis Alvarez on the fall of a ∼20 km asteroid as the cause of the K/T mass extinction, not only the scientific community, but the lay people at large have become fully aware of this threat. However, there is no general agreement about *how* the threat should be faced. The use of nuclear weapons in space, as well as the necessary use of missiles, is in the hand of the military and all these activities are covered by secret. Also, the cold war ended too recently to let the general public perceive that by only by launching missiles against them it will be possible to divert dangerous asteroids and comets from their collision path against the Earth. Even less perceived is the fact that this "deflection" of asteroids will be better achieved if the missiles are launched not from the surface of the Earth, but from other points in space, that is from the possible future space bases for Planetary Defense. In this paper we wish to point out that the best locations for such Planetary Defense space bases will be up to four out the five Lagrangian Points (also called Libration Points) that do exist within the sphere of attraction of the Earth because of the combined Earth–Moon attraction. Finally, in this paper we are going to prove mathematically that *confocal trajectories* for missiles launched from the Lagrangian points L3 and L1 against dangerous asteroids are the *best* trajectories, since as they insure that the asteroid will be hit *orthogonally* to its own path.

(2) The need for doing SETI (the search for extraterrestrial intelligence) and radioastronomy from an environment totally free from human-made RFI (radio frequency interference) is much less perceived by the scientific community, not to mention the people at large. This is primarily because non-scientific prejudices have prevented for centuries the recognition that forms of alien life could possibly exist on planets orbiting other stars in the Galaxy. Also, the scientific community itself was rather late to recognize the possibility of alien life in space: only in 1982 was Commission 51 of the International Astronomical Union created to study Bioastronomy and SETI on the suggestion of outstanding scientists like Frank Drake (who had started the experimental SETI searches back in 1960) and Carl Sagan (who had designed for NASA in the 1970s the famous Voyagers messages "to be read by ETs"). Nowadays, however, SETI from the surface of the Earth is becoming harder and harder to pursue because of RFI, the radio frequency interference produced by the growth of civilization on Earth, that is progressively blinding larger and larger portions of the electromagnetic spectrum to the very sensitive SETI spectral analyzers. Is SETI doomed to die because of man-made RFI? No, if we going to take advantage of the farside of the Moon, the only RFI-free environment in the vicinity of the Earth because the Moon's body acts as a shield against the RFI coming from the Earth. In 1994 the late French radioastronomer, Jean Heidmann (1923–2000), selected crater Saha, on the farside of the Moon, as the "best" location to set up a radio antenna to do SETI and any kind of radioastronomical searches in an environment totally free from man-made RFI [1]. Until his death on July 3, 2000, he furtherly elaborated on this scheme, extending it so as to encompass the use of the five Lagrangian points of the Earth–Moon system [2]. So, it should not be surprising that, in this paper, Heidmann's schemes are furtherly elaborated still, and the use of another crater instead of Saha is proposed for the first time: this is crater Daedalus, located at 180° of longitude East and 5° of latitude South on the farside of the Moon. Crater Daedalus has a peculiar advantage: it is almost exactly located at the Earth's antipode on the Moon. It is thus evident that using crater Daedalus instead of Saha would allow free use of the Lagrangian point L5, rather than having it kept free from anything, as suggested by Heidmann in Ref. [2]. Consequently, a new space mission is suggested in this paper for the first time: dubbed "RadioMoon", it consists in landing a phased array inside crater Daedalus and having another relay satellite orbit the Moon in the equatorial plane in order to collect the data when above

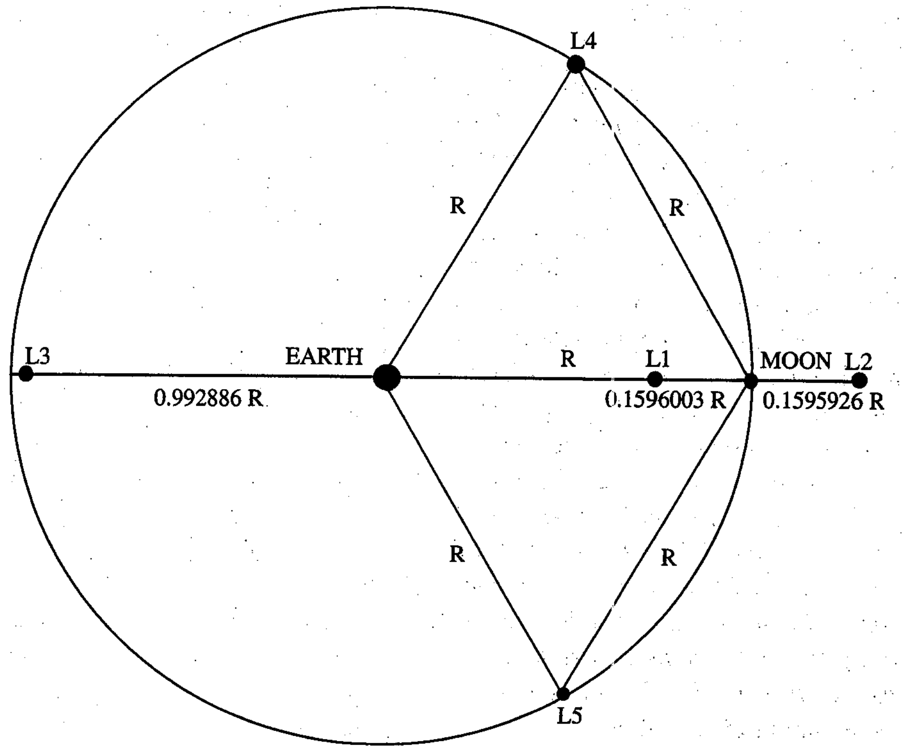

Fig. 1. The five Lagrangian points of the Earth–Moon system and their distances from Earth and Moon expressed in terms of R, the Earth–Moon distance (supposing the Moon orbit circular, in the first approximation).

Daedalus, and send them back to Earth when above the Earth-facing side of the Moon.

In conclusion, this paper aims at merging the two apparently unrelated needs for Planetary Defense and RFI-free Environment into a single, unified vision. This is achieved by assigning neatly defined tasks to each of the five Lagrangian points as well as to the farside of the Moon.

2. A SHORT REVIEW ABOUT THE FIVE LAGRANGIAN POINTS

Let us start by reviewing what the five Lagrangian points are and where they are located, even if this is well-known material to astrophysicists and space scientists alike (see, for instance, the excellent paper [3] written in 1987 by the American astrodynamicist David W. Dunham).

Historians of science tell us that the year was 1772 when mathematician Joseph Louis Lagrange (born in Turin on 25 January 1736 and died in Paris on 10 April 1813) demonstrated that there are five positions of equilibrium in a rotating two-body gravity field (Refs. [4] and [5] give the full account). Out of these five "Lagrangian points" (also called "Libration points"), three are situated on the line joining the two massive bodies, and are nowadays called "colinear points", or L1, L2 and L3, as shown in Fig. 1 for the Earth–Moon system. The other two (called L4 and L5) form equilateral triangles with the two massive bodies, and so are called "triangular points".

The locations of the three colinear points L1, L2 and L3 are found as the real roots of an algebraic equation of the fifth degree, originally due to Lagrange, that can only be solved by resorting to Taylor series expansions. Fortunately, the relevant three different Taylor expansions converge rapidly, so one may take into account just three terms in each Taylor expansion to get approximations that are quite satisfactory numerically. Here we just confine ourselves to stating that, assuming for the Earth–Moon distance the numerical value of $R = 384,401$ km, then:

(1) The distance between the Moon and the Lagrangian point L1 equals $0.1596003R$, that is 61350.317208 km. Consequently the Earth-to-L1 distance equals $0.8403997R$, that is 323050.482792 km.
(2) The distance between the Moon and the Lagrangian point L2 equals $0.1595926R$, that is 61347.568938 km.
(3) The distance between the Earth and the Lagrangian point L3 equals $0.992886R$, that is 381666.370650 km.

3. CONFOCAL TRAJECTORIES FOR THE BEST DEFLECTION OF DANGEROUS ASTEROIDS

This section is devoted to the mathematical theory of *confocal conics* as the *best trajectories* for deflecting dangerous asteroids by virtue of missiles launched from either of the two colinear Lagrangian points L1 and L3. The triangular points L4 and L5 are excluded from this theory because the trajectories of missiles launched from them is not planar, and so much more complicated. Also, the Lagrangian points L1 and L2 of the Sun–Earth system are excluded from the following considerations, inasmuch as they would require the theory of perturbations. In conclusion, we just consider the *Planetary Defense from the nearest two Lagrangian points, L1 and L3 and in the plane passing through the Earth-Moon axis and through the incoming asteroid or comet. This is always allowed by the cylindrical symmetry around the Earth–Moon axis if one considers L1, L2, L3 only.*

Start from the equation of the ellipse

$$\frac{x^2}{a_{\text{ell}}^2} + \frac{y^2}{b_{\text{ell}}^2} = 1, \tag{1}$$

where

$$a_{\text{ell}}^2 = b_{\text{ell}}^2 + c_{\text{ell}}^2 \tag{2}$$

and

$$0 \leqslant e_{\text{ell}} = \frac{c_{\text{ell}}}{a_{\text{ell}}} < 1 \tag{3}$$

and the equation of the hyperbola

$$\frac{x^2}{a_{\text{hyp}}^2} - \frac{y^2}{b_{\text{hyp}}^2} = 1, \tag{4}$$

where

$$c_{\text{hyp}}^2 = a_{\text{hyp}}^2 + b_{\text{hyp}}^2 \tag{5}$$

and

$$e_{\text{hyp}} = \frac{c_{\text{hyp}}}{a_{\text{hyp}}} > 1. \tag{6}$$

If the ellipse and the hyperbola have the same value for c, namely if

$$c_{\text{ell}} = c_{\text{hyp}} = c, \tag{7}$$

then the ellipse and the hyperbola are said to be "confocal" (or "omofocal"), inasmuch as the two focal points located at $(-c, 0)$ and $(c, 0)$ are common to both. Because of eqns (7), (3) and (6) the above confocality definition translates into the equation

$$a_{\text{ell}} e_{\text{ell}} = a_{\text{hyp}} e_{\text{hyp}}. \tag{8}$$

Actually, by doing so, we have really defined two families of confocal conics. One is the family of ∞^1

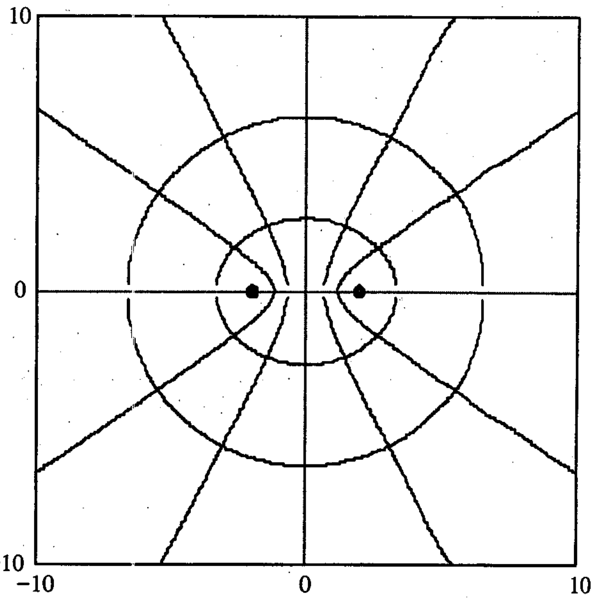

Fig. 2. The two families of ∞^1 confocal ellipses and ∞^1 confocal hyperbolas.

confocal ellipses, and the other is the family of ∞^1 confocal hyperbolas. In fact, each one of the confocal ellipses has a different value of both a_{ell} and e_{ell}, but the latters' product always equals the constant value c (as from the confocality condition (8)) so that you either assign a_{ell} and determine e_{ell} by virtue of eqn (8), or the other way round. The same for the hyperbolas. Figure 2 shows two confocal ellipses and two confocal hyperbolas (the "missing" vertical parts in the graphs are just because the computer does not know what infinity is!).

What is the "great" property of confocal conics? It is that the any pair of different confocal conics, namely one ellipse and one hyperbola, always intersect each other at angles of 90°. In other words, the family of ellipses (1) and the family of hyperbolas (4), when related by the confocality condition (8), form two families of *orthogonal trajectories*. This is a well-known result proven in any textbook of elementary analytical geometry. Not to leave the reader with doubts, however, we just hint the proof in a few lines! Call (x_0, y_0) the intersection point of the two conics (actually there are four such intersections for each pair of conics, but pretend you do not know about it!). Then, high-school students know that the tangent line to the ellipse at point (x_0, y_0) has the equation

$$\frac{xx_0}{a_{\text{ell}}^2} + \frac{yy_0}{b_{\text{ell}}^2} = 1 \tag{9}$$

and the tangent line to the hyperbola at point (x_0, y_0) has the equation

$$\frac{xx_0}{a_{\text{hyp}}^2} - \frac{yy_0}{b_{\text{hyp}}^2} = 1. \tag{10}$$

Solving the last two equations with respect to y, one finds the two angular coefficients of these tangent lines. Multiplying then these two angular coefficients, one gets, after some reductions, -1 as the result. This shows that the tangents to the ellipse and to the hyperbola are orthogonal to each other.

Is all this of any importance for deflecting dangerous asteroids?

Yes — is our answer — and here follows the sequence of logical steps leading towards the application of confocal conics as the *best* trajectories for missiles shooted from the Lagrangian points L3 and/or L1:

(1) Consider only one of the two focuses (or "foci", in Latin), namely the one "on the right". Imagine the Earth is there. Then both the confocal ellipse and the confocal hyperbola are physical trajectories (paths) that moving bodies around the Earth follow naturally, since this is just Kepler's First Law. But, which body is following which path?

(2) An asteroid or comet arrives from infinity, namely from outside the sphere of influence of the Earth. So, it can only follow a *hyperbolic* trajectory with respect to the Earth, with the focus of this hyperbola located just at the center of the Earth (at least in the first approximation, to which we confine ourselves here). Also, the incoming asteroid or comet is to be regarded as "dangerous" only if its path crosses the surface of the Earth, namely if the perigee of its hyperbolic trajectory is smaller than the Earth radius: $c_{\text{hyp}} \leqslant R_{\text{Earth}}$.

(3) What is the counterpart of the ellipse confocal to the asteroid's hyperbola? Our answer is: the confocal ellipse is the physical trajectory of a missile launched against the incoming dangerous asteroid from any point in space, but better from the two colinear Lagrangian points, L1 and L3, located each on one side of the Earth "for better defense". Points L4 and L5 could also be used, but the relevant missile's orbit calculations would be more involved as three dimensional. Notice also that L2 is to be excluded from becoming a missile base because not visible from the Earth (the Moon hides it) and because we will show later that L2 will better being kept free of radio-emitting devices to allow optimal SETI be done from the farside of the Moon (see Sections 4 and 5 of this paper). The selection of the colinear Lagrangian points L1 and L3 as space bases for missiles is now self-evident: they ensure the *cylindrical symmetry of the problem around the Earth–Moon axis*. So, the direction in space from which the asteroid is arriving towards the Earth becomes *irrelevant* (at least in this first-order approximation): we will just be studying confocal orbits in the plane passing through the Earth–Moon axis and the asteroid. Additionally, the merit of all the Lagrangian points is that they are "fixed" in the Earth–Moon system, in that they keep their positions unaltered with respect to the Earth and the Moon at all times.

(4) But being confocal, the missile's ellipse is also automatically *orthogonal* to the asteroid's hyperbola, meaning that the collision of the missile with the asteroids always occurs at a right angle with the asteroid's path. This is really *the best* we can hope for in order to deflect the asteroid, since the missile's *full* momentum is then transferred to the asteroid *sidewise*.

(5) Finally, if one missile fails to deflect the asteroid's path in a sufficient amount, we can always send one or more missiles again along the new ellipse that is confocal to the new and slightly deflected asteroid's hyperbolic path. This is because confocal conics are actually two *families* of ∞^1 trajectories. So, once again, the mathematical representation of the trajectories in the game by virtue of *confocal* conics matches perfectly with the physical problem of diverting dangerous asteroids and comets!

Having ascertained the above five facts, we now face a mathematical problem: given the trajectory of the incoming asteroid, that is given its confocal hyperbola, can the relevant confocal ellipse departing from L3 or L1 be determined uniquely?

Yes — is the answer — as we now prove.

Start from the polar equations, of the ellipse

$$r_{\text{ell}} = \frac{a_{\text{ell}}(1 - e_{\text{ell}}^2)}{1 + e_{\text{ell}} \cos(\phi_{\text{ell}} - \omega_{\text{ell}})} \tag{11}$$

and of the hyperbola

$$r_{\text{hyp}} = \frac{a_{\text{hyp}}(1 + e_{\text{hyp}}^2)}{1 + e_{\text{hyp}} \cos(\phi_{\text{hyp}} - \omega_{\text{hyp}})}. \tag{12}$$

The problem's given data is the asteroid's hyperbolic path, whose three elements a_{hyp}, e_{hyp} and ω_{hyp} are here supposed to have been previously determined by astronomical observations and/or by radar detection to a sufficient accuracy. The problem's unknowns are the three elements a_{ell}, e_{ell} and ω_{ell} of the elliptical missile trajectory confocal (and so automatically orthogonal) to the asteroid's hyperbola and leaving from one of the three colinear Lagrangian points. In other words, we have to find three unknowns, and so we need three equations relating them. These three equations are:

(1) The confocality condition (8), that holds just the same in both cartesian and polar coordinates.
(2) The fact that we use only one branch of the hyperbola rather than both branches. This only branch is the one whose apsis is "facing" the confocal ellipse's apsis around the common focus, so these two apses are located on the *opposite* sides of the focus, namely on the opposite sides of the Earth. In mathematical terms, this description amounts to saying that the argument of the perigee of the ellipse differs from the argument of the perigee of the hyperbola exactly by an angle of 180°, that is

$$\omega_{\text{ell}} = \omega_{\text{hyp}} + \pi. \tag{13}$$

(3) The third equation translates the requirement that the missile base has been located at either of the colinear Lagrangian points L1 and L3. To fix ideas, suppose that this point is L3 (the point "on the far opposite direction to the Moon" in Fig. 1) and denote by R_{L3} the distance between the Earth and L3 (obviously known). The polar coordinates of L3 are then (R_{L3}, π) and the requirement that the missile is launched from L3 translates in replacing these coordinates inside the polar equation of the ellipse (11), yielding

$$R_{\text{L3}} = \frac{a_{\text{ell}}(1 - e_{\text{ell}}^2)}{1 + e_{\text{ell}}\cos(\pi - \omega_{\text{ell}})}. \tag{14}$$

The remaining calculations are just all the reductions necessary to solve the three simultaneous equations (8), (13) and (14) with respect to the three unknowns a_{ell}, e_{ell} and ω_{ell}. Since eqn (13) is already solved for ω_{ell}, we simply have to replace eqn (13) into eqn (14), getting

$$R_{\text{L3}} = \frac{a_{\text{ell}}(1 - e_{\text{ell}}^2)}{1 + e_{\text{ell}}\cos(\omega_{\text{hyp}})}. \tag{15}$$

Next we must solve the remaining two simultaneous equations (8) and (15) for a_{ell} and e_{ell}. Then, replacing eqn (8) into (15), one gets a second degree algebraic equation in the only unknown e_{ell} that we are not going to write here. Solving this equation for e_{ell}, one finds two roots, one of which must be discarded since negative. The other root, positive, is the requested expression for the eccentricity of the ellipse:

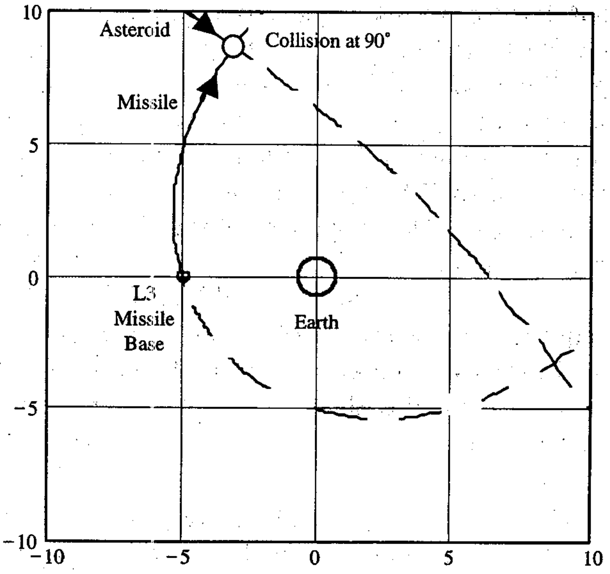

Fig. 3. Asteroid missing the Earth, and elliptical path of the missile shooted against it from L3. The orthogonality of the two paths at their collision point is evident.

$$e_{\text{ell}} = \frac{\sqrt{R_{\text{L3}}^2 + 4R_{\text{L3}}a_{\text{hyp}}e_{\text{hyp}}\cos(\omega_{\text{hyp}}) + 4a_{\text{hyp}}^2e_{\text{hyp}}^2} - R_{\text{L3}}}{2[R_{\text{L3}}\cos(\omega_{\text{hyp}}) + a_{\text{hyp}}e_{\text{hyp}}]}. \tag{16}$$

This, replaced into the confocality condition (8), finally yields the semi-major axis of the ellipse

$$a_{\text{ell}} = \frac{2[R_{\text{L3}}\cos(\omega_{\text{hyp}}) + a_{\text{hyp}}e_{\text{hyp}}]a_{\text{hyp}}e_{\text{hyp}}}{\sqrt{R_{\text{L3}}^2 + 4R_{\text{L3}}a_{\text{hyp}}e_{\text{hyp}}\cos(\omega_{\text{hyp}}) + 4a_{\text{hyp}}^2e_{\text{hyp}}^2} - R_{\text{L3}}}. \tag{17}$$

and the problem is solved. The position of the point of collision between the missile and the asteroid is found as by-product by firstly replacing eqns (16) and (17) into the equation of the ellipse (11), that yields the anomaly of the collision point. Replacing this anomaly into the hyperbola (12), one finally obtains the distance of the collision point from the Earth.

Figure 3 shows a first numerical example (in arbitrary units not to scale with the actual Earth–Moon system values): the incoming asteroid's is missing the Earth (represented by the larger circle located at the origin), but is of course deflected along an hyperbola. Then the missile shooted from the Lagrangian point L3 (the smaller circle on the left) can hit the asteroid before it approaches the Earth, colliding with it at an orthogonal angle.

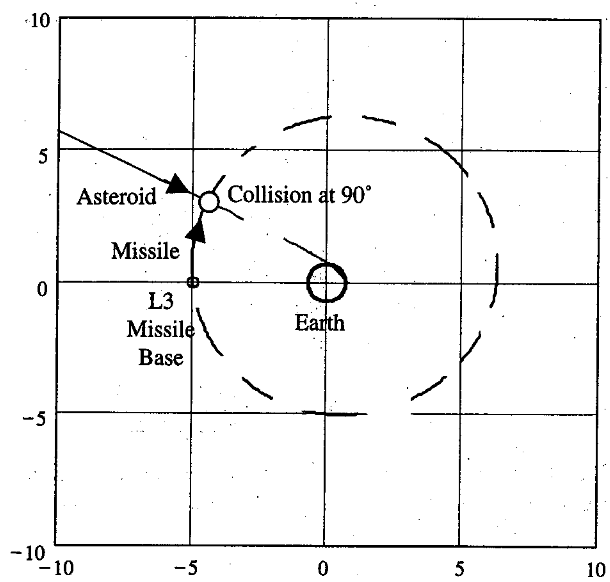

Fig. 4. Asteroid hitting the Earth. Before it reaches the Earth, it could be diverted by the collision of a missile shooted from L3 along the shown ellipse, orthogonal to the asteroid's path for the maximum deflection.

Finally, Fig. 4 shows the feared asteroid's impact against the Earth. But a missile shooted from the Lagrangian point L3 along the shown ellipse, confocal to the asteroid's hyperbola, could have rescued humankind beforehand!

4. POLITICAL PROBLEMS FOR PLANETARY DEFENSE FROM THE LAGRANGIAN POINTS

The Cold War ended about ten years ago, but many people's minds are still too much in the Cold War attitude. Since nuclear weapons in space are forbidden by international treatises, a Proposal to locate missiles with possible nuclear warheads at the Lagrangian points L3 and L1 would immediately be perceived as an attempt to revive the Cold War. So, it is realistic to take for granted that any such a Proposal, if put forward officially to any country's political institutions, would immediately be rejected by politicians as well as by the public at large. Just think of all the problems that NASA and ESA are having with ecologists just in order to put radioactive thermal generators (RTGs) aboard their spacecrafts. Ecologists against RTGs actually support a narrow-minded view of ecology, based on the oversimplified belief that whatever is "nuclear" is "dangerous". This is the heritage of the Cold War and of all wars that went before it.

Still the problem of doing Planetary Defense from space does exist.

The threat of asteroids and comets creating havoc on the Earth's surface is a real threat, as it was quite well proven by the Tunguska event of 1908. However, (fortunately!) the Tunguska disaster took place in a lonely forest of Siberia, and so there were no casualties, and, on the other hand, back in 1908 not even the scientific community was ready to accept that such an disaster could possibly occur, not to mention that governments and lay people were not ready at all to learn the Tunguska lesson. So, everything went on just as if nothing had happened at Tunguska, until the first scientists took some notice in 1927.

All this shows well that humankind still is not yet ready to face the threat of dangerous asteroids and comets. Only when humans will stop planning and conducting big wars among themselves, will the governments have more time to think about the new danger coming from space. And ecologists will get mature to the point of not hampering their governmental agencies to put up missiles and weapons in space if these are to prevent dangerous asteroids and comets from killing the whole of humankind, including the ecologists themselves!

In conclusion, this new *conscience of a single fate for the whole of humankind* will finally take over in the vast majority of humans, and prepare them to the deep changes of new millennium.

If the following leap of imagination is not too daring even for the most open-minded, we claim the most profound change of the future can only be the contact between humans and other extraterrestrial beings. To a high degree of likeliness, statistics about the 300 billions stars in this Galaxy tell us that "someone else" *must* inhabit our Galaxy, just as well as we do. Quite simply, we have not met them yet in the year 2000. This may well be because our technology is so backward compared to theirs, or because just our backwardness means that we are of no interest to them at all.

So, ETs enter the scene now.

And "Finding ETs" is the goal of SETI, the search for extraterrestrial intelligence, already pursued since 1960 from the surface of the Earth by scientists of several countries and by virtue of the largest radiotelescopes.

In the years of this new century, SETI will be best done from the farside of the Moon.

5. JEAN HEIDMANN'S CRATER SAHA PROPOSAL (1994) FOR RFI-FREE SEARCHES

This paper also intends to be a tribute to the late French IAA Academician and SETI Radio Astronomer, Jean Heidmann, born in Alsace, 18 May 1923, and died in Paris, 3 July 2000. Highlights about his works and life can be found at the SETI Institute web site: *http://www.seti-inst.edu/general/jean_heidmann.html*.

Fig. 5. Jean Heidmann (1923–2000), SETI pioneer and supporter of the inviolability of the Moon farside.

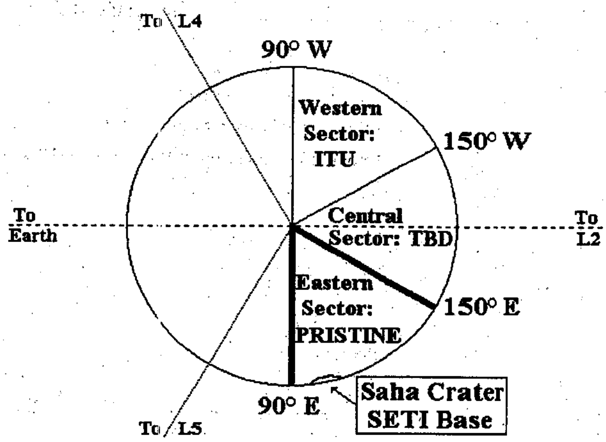

Fig. 6. Jean Heidmann's vision of the farside of the Moon with the Saha crater for SETI and radioastronomy.

Figure 5 shows Jean Heidmann in recent years. Heidmann understood earlier than many of his contemporaries that an incisive action, both cultural (inspired by the International Academy of Astronautics) and legal (inspired by the International Institute of Space Law), should have already been undertaken in order to protect the farside of the Moon from uncontrolled commercial, industrial and possibly military exploitation in the new millennium. In his last paper [2]. Heidmann sought to establish at least a fair balance between the conflicting interest of:

(1) the Moon exploiters from the industry, from future "Moon Realtors" willing to settle the Moon, and maybe from the military, and
(2) the interest of the "pure" scientists, namely those aware that installing human bases on the farside of the Moon would deprive humankind of the only RFI-free land still available in the neighborhood of the Earth.

Figure 6 shows a map of the Moon as seen from its North Pole with the different "colonization regimes" proposed by Heidmann in Ref. [2]. We see that:

(1) The near side of the Moon is left totally free to activities of all kinds: scientific, commercial and industrial.
(2) The farside of the Moon is divided into three thirds, that is three sectors covering 60° in longitude each, out of which:
   (a) The Eastern Sector, in between 90°E and 150°E, must be kept totally free from human exploitation, or, as Heidmann puts it, is kept in its "pristine" radio environment, totally free from man-made RFI. This Sector is where crater Saha is, a ~100 km crater located in between 101°E and 105°E and around 2° of latitude South, surrounded by a 3000 m high circular rim. Since 1994 (when he published his crater Saha Proposal [1], but yet not the partition of the farside into three thirds, given only in 2000 in Ref. [2]) up to his death on 3 July 2000, Heidmann maintained that crater Saha was the best location on the farside of the Moon for establishing a radio station capable of doing SETI and general radioastronomy. No one objected to his selection.
   (b) The Central Sector, in between 150°E and 150°W, is left in a regime still to be defined (tbd).
   (c) The Western Sector, in between 90°W and 150°W, can be used for installation of radio devices, but only under the control of the International Telecommunications Union (ITU-regime).

This year-2000 partition of the farside into thirds Heidmann inferred basically from the position of the L4 and L5 triangular Lagrangian points. In fact:

(1) The Eastern Sector is exactly opposite to the direction of the Lagrangian point L4, and so the body of the Moon completely shields the Eastern Sector from RFI produced at L4. Thus, L4 is fully "colonizable" in Heidmann's 2000 Proposal [2].
(2) On the contrary, L5 is not colonizable at all in Heidmann's 2000 Proposal because it is seen between 41° and 45° above the horizon of Saha.

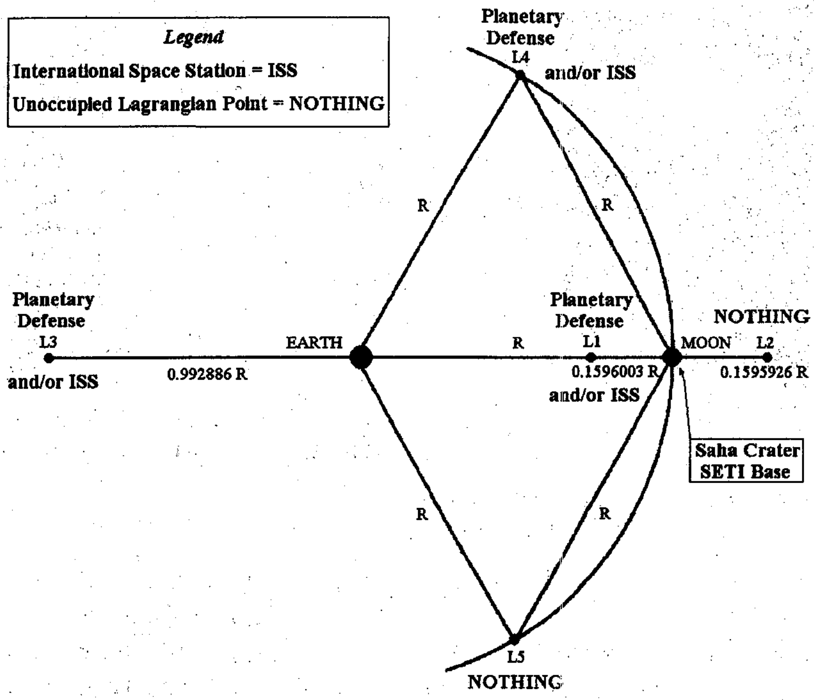

Fig. 7. Jean Heidmann's year-2000 vision [2] of the utilization of the Moon and the Lagrangian points. Planetary Defense as a task for bases located at the Lagrangian points has been added by the author of this paper.

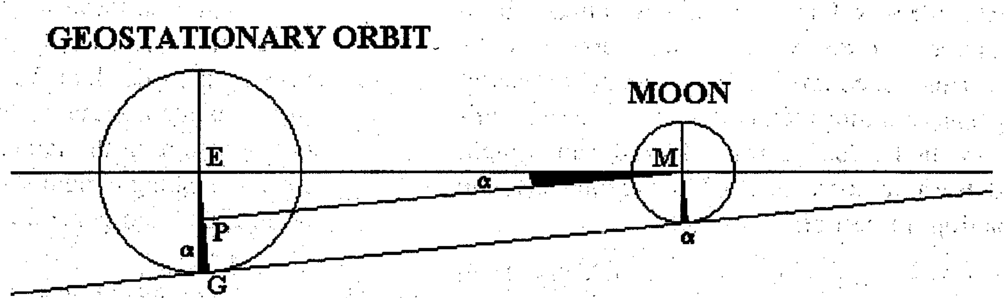

Fig. 8. How Heidmann selected crater Saha in 1994 as the farside equatorial crater *closest to the limb* but still shielded from the flood of radio waves emitted by telecommunications satellites in Earth's *geostationary orbit*.

(3) And, of course, L2 is also not colonizable at all, since it is seen about 11–15° above the horizon of Saha. Any RFI-producing device located at L2 would flood the whole of the farside, and must be ruled out.

Figure 7 summarizes Heidmann's year-2000 vision of the utilization of the Moon and of the five Lagrangian points. While Heidmann only envisaged the International Space Station (ISS) or satellites of all kinds (scientific and/or commercial) as the utilizers of the Lagrangian points L1, L3 and L4, the author of this paper has added on Fig. 7 the Planetary Defense as an additional task to be possibly accomplished at these Lagrangian points.

But why did Heidmann select just *crater Saha*, and not another crater, back in his first 1994 paper? Because he had computed that Saha was the *nearest crater to the limb still not flooded by the RFI produced by satellites in geostationary orbit around the Earth*. Let us prove this geometric theorem right now, since it is basic for the selection of Saha or of another equatorial crater instead. Consider Fig. 8, where only the Earth's geostationary orbit and the Moon have been shown (the Earth's body is irrelevant).

We want to compute the small angle α beyond the limb (the limb is the meridian having longitude 90°E on the Moon) where the radio waves coming from the Earth's geostationary orbit still reach, that is, they become tangent to the Moon's sphere. The angle $\lambda = \alpha + 90^\circ$ we shall call "terminal longitude" of the radio waves coming from the satellite in a circular orbit with a radius R around the Earth because no radio wave can hit the Moon surface at longitudes higher than this terminal longitude.

To find α, we firstly draw the straight line tangent to the Moon's sphere from G, the point tangent to the circular geostationary orbit. This straight line forms a right-angled triangle with the Earth–Moon axis, EM, having its right angle at point G. Next, consider the straight line parallel to the foregoing straight line from the Moon center M and intersecting the EG segment at a certain point P. Once again, the triangle EPM is right-angled, with its right angle at point P, and it is similar to the foregoing triangle. So, the angle α we want to compute is now equal to the EMP angle. But this can be found, since we know:

(1) The Earth–Moon distance $EM = D_{Earth-Moon}$. Since the Moon's orbit is elliptical, let us assume for this distance the worst case, that is the case when the Moon is at its perigee: the Earth–Moon distance equals then about 356410 km.
(2) The EP segment equals the $EG = R$ segment minus the Moon radius, R_{Moon}
(3) Using Pythagoras' theorem one finds

$$PM = \sqrt{(EM)^2 - (EP)^2}. \qquad (18)$$

(4) The tangent of the requested angle α is then given by

$$\tan\alpha = \frac{EP}{PM} = \frac{EP}{\sqrt{(EM)^2 - (EP)^2}}. \qquad (19)$$

In conclusion, inverting eqn (19) and making the substitutions described at (1), (2) and (4), one gets the terminal longitude λ of radio waves on the Moon farside (between 90°E and 180°E) emitted by a telecommunication satellite circling the Earth at a distance R from its center:

$$\lambda = \operatorname{atan}\left(\frac{R - R_{Moon}}{\sqrt{D^2_{Earth-Moon} - (R - R_{Moon})^2}}\right) + \frac{\pi}{2}, \qquad (20)$$

where the independent variable R can range only between 0 and the maximum value that does not make the radical in eqn (20) become negative, that is

$$0 \leqslant R \leqslant D_{Earth-Moon} + R_{Moon}. \qquad (21)$$

In mathematical terms, eqn (21) shows that the $\lambda(R)$ curve has a vertical asymptote for $R \to (D_{Earth-Moon} + R_{Moon})$, and the abscissa of this vertical asymptote is $\lambda = 180°$.

Replacing into eqn (20) the value of the geostationary radius, $R = 42241.096$ km, one finds for the corresponding Moon farside terminal longitude λ the value

$$\lambda = 96.525°. \qquad (22)$$

This is how Heidmann came to propose crater Saha: he just used the above (unpublished, but obvious) argument to compute that the longitude of the needed crater had to be higher than the 96.525° value given by eqn (22). Then he looked at the NASA Lunar Planning Charts of 1971, and, allowing a little more tolerance of about 5° in longitude for further shielding by the Moon's body, finally declared in Ref. [1] that Saha was the "best" crater to establish a Lunar SETI base.

Astronautically speaking, however, it soon became clear to Heidmann, to the author of this paper, and to others, that the big problem was then *how* to establish the SETI base inside Saha. Heidmann did not know how to answer the question, but he did not exclude that his SETI Moon at Saha base could have been set up and looked after by *men on the Moon*, as he mentions in his paper [6, p. 662], when he says: "The lunar region closest to Saha in view of the Earth is the western part of Mare Smythii. This region, until eventual confirmation of water ice deposits at the South pole, is a favourite for a main lunar base, man-tended or more probably purely robotic. Material connection to Saha can be provided by a 350 km long trail, lightly bulldozed in the regolith, with slopes smaller than 5°, along which rovers could insure transportation, deployment and maintenance of radio instruments. It appears that telecommunications up to Saha for robotic telepresence and observational data flow could be insured by depositing three data relays along the route (then Heidmann goes on to forbid the use of L2 for any data relay, of course)".

Others, including this author, tried to figure up space missions capable of landing both the SETI antenna in Saha and the relay antenna in Mare Smythii, and link them up to each other for data transmissions, in a *purely robotic fashion* [7]. So, for six years (1994–2000) no one within the IAA, or within the astronomical community, or even within the scientific community at large, thought of questioning Saha crater as the "best" possible crater.

With all due respect to Heidmann's memory, however, suggesting another crater instead of Saha is precisely what this author is going to do in the next section of this paper.

6. SELECTING CRATER DAEDALUS AT 180°E FOR ALL RFI-FREE SEARCHES

The author of this paper claims that Heidmann was too optimistic in excluding that telecommunications satellites will ever be put into orbits around the Earth *higher than the geostationary orbit of* 42241.096 km.

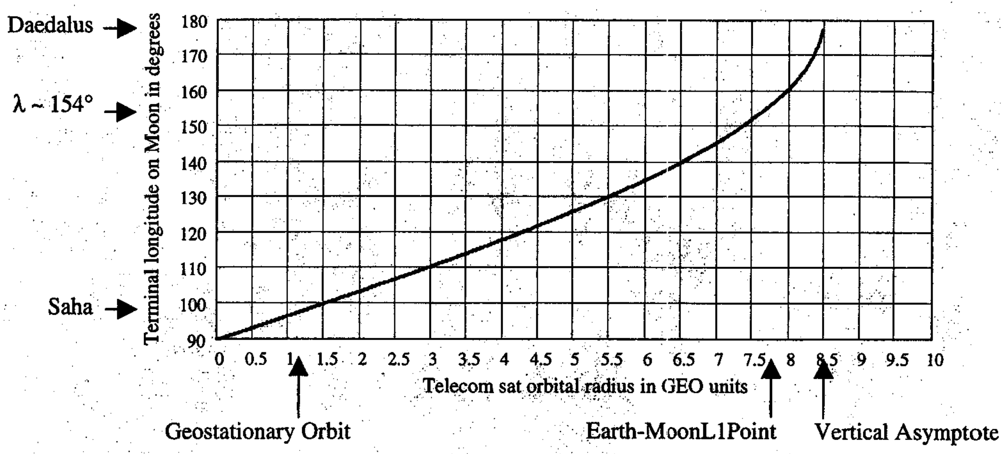

Fig. 9. Terminal longitude (vertical axis) on the Moon farside of the region still flooded by radio waves emitted from a telecommunications satellite put in a circular orbit around the Earth at a distance R (horizontal axis) in units of the Earth's geostationary radius (42241.096 km).

In other words, this author claims that the time will come when commercial wars among the big industrial trusts running the telecommunications business by satellites will lead them to grab more and more space around the Earth, pushing their satellites into orbits with apogee much higher than the geostationary one, with the result that *crater Saha will be blinded as soon as the companies decide to go higher than the geostationary orbit.*

The last remark is important for the SETI community. If we, the supporters of SETI, bet everything on a SETI base located at Saha, we may loose everything.

A "safer" crater other than Saha must be selected further East along the Moon equator.

How much further East?

The answer if given by the diagram in Fig. 9, based on eqn (20). The horizontal axis shows the radius of a circular orbit for telecommunication satellites around the Earth, for convenience measured here in units of the geostationary radius equal to 42241.096 km. The vertical axis plots the corresponding terminal longitude on the Moon farside, namely the highest longitude still blinded on the Moon farside, in degrees. Heidmann's value (22) of $96,525^\circ$ corresponds to the value 1 on the horizontal axis, and this is how Saha was selected.

The vertical asymptote predicted by eqn (21) shows up in Fig. 9 as the "upgoing right branch". This shows that, if we only keep into account eqn (20) (as Heidmann did) the maximum distance from the Earth's center for these telecommunications satellites is about 8.479 times the geostationary radius, corresponding to a circular orbital radius of 358, 148 km. Was a telecommunications satellite put in such a circular orbit around the Earth, its radio waves would flood Moon longitudes as high as about $\sim 175^\circ$ or more.

However, here the surprise comes.

We did not take the Lagrangian points into account yet!

So, it will never be possible to put a satellite in a circular orbit around the Earth at a distance of 358, 148 km, simply because this distance already lies beyond the distance of the nearest Lagrangian point L1, that is located at 323, 050 km (Lagrangian points are, by definition, the points of zero orbital velocity in the two-body problem!).

So we are now led to wonder: what is the Moon farside terminal longitude corresponding to the distance of the nearest Lagrangian point, L1? The answer is given by eqn (20) upon replacing $R = 323,050$ km, and the result is

$$\lambda = 154.359^\circ. \tag{23}$$

In words, this sounds:

the Moon Farside Sector in between 154.359E *and* 154.359W *will never be blinded by RFI coming from satellites orbiting the Earth alone.*

This is the most important result of this paper as far as SETI is concerned.

And once again, let us put all this in different words: the *limit* of the blinded longitude as a function of the satellite's orbital radius around the Earth is 180° (E and W longitudes just coincide at this meridian, corresponding to the "change-of-date line" on Earth). But this is the *antipode* to Earth on the Moon surface, that is the point exactly opposite to the Earth direction on the other side of the Moon. And our theorem simply proves that the

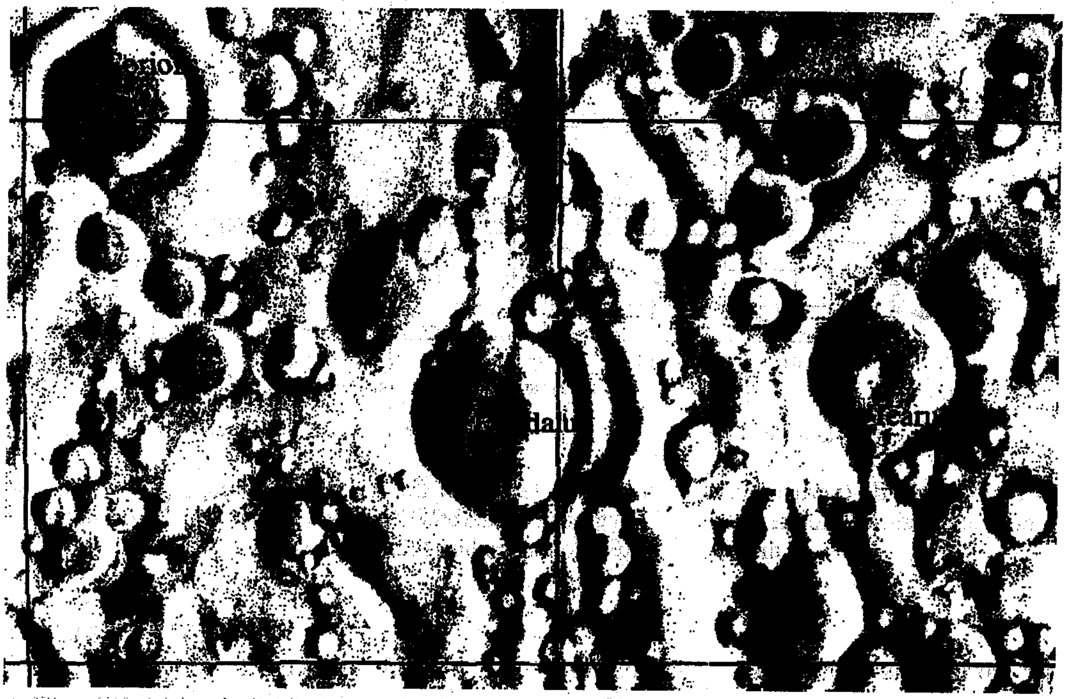

Fig. 10. Crater Daedalus, the crater located nearest to the Earth's antipode on the farside of the Moon. In this figure are shown the Moon's equator (horizontal line at the top of the figure) and the 180°E meridian (the central vertical line). They cross at the Earth's antipode but the Moon's soil there is too rugged to place a base. Thus, one is forced to select crater Daedalus, located about 5° South of the equator but crossed by the 180°E meridian, as the best possible farside Moon base close to the Earth's antipode. Crater Daedalus is about 100 km in diameter, just as crater Saha is.

antipode is the most shielded point on the Moon surface from radio waves coming from the Earth. An intuitive and obvious result, really.

So, where are we going to locate our SETI farside Moon base?

Just take a map of the Moon farside and look. Figure 10 shows the antipode's region as depicted on the Hallwag map of the Moon (dated 1982, [8]). One notices that the antipode's region (at the crossing of the central meridian and of the top parallel in the figure) is too a rugged region to establish a Moon base. Just about 5° South along the 180° meridian, however, one finds a large crater about 100 km in diameter, just like Saha. This crater is called Daedalus. So, this author proposes here to establish the first SETI base on the Moon just inside crater Daedalus, the most shielded crater of all on the Moon from the radio garbage coming from the Earth!†

†(Just kidding) Were we living in the Middle Ages, crater Daedalus would be the ideal place to set up a monastery! So secluded from the mundane distractions of the Earth! But we live in the 2000's, and so today's SETI monks can hardly fail to recognize that this is the most quiet place to let us get in touch with the "Superior Being(s)"!.

7. THIS AUTHOR'S VISION OF PLANETARY DEFENCE AND RFI-FREE SEARCHES

Let us replace the 154.359° of eqn (23) with the simpler value of 150°. This matches perfectly with the need for having the borders of the Pristine Sector making angles orthogonal to the directions of L4 and L5. The result is this author's vision of the farside of the Moon, shown in Fig. 11.

Figure 11 shows a map of the Moon as seen from its North Pole with the different "colonization regimes" proposed by this author. We see that:

(1) The near side of the Moon is left totally free to activities of all kinds: scientific, commercial and industrial.

(2) The farside of the Moon is divided into three thirds, that is three sectors covering 60° in longitude each, out of which:

  (a) The Eastern Sector, in between 90°E and 150°E, can be used for installation of radio devices, but only under the control of the International Telecommunications Union (ITU-regime).

  (b) The Central Sector, in between 150°E and 150°W, must be kept totally free from human exploitation, namely it is kept in

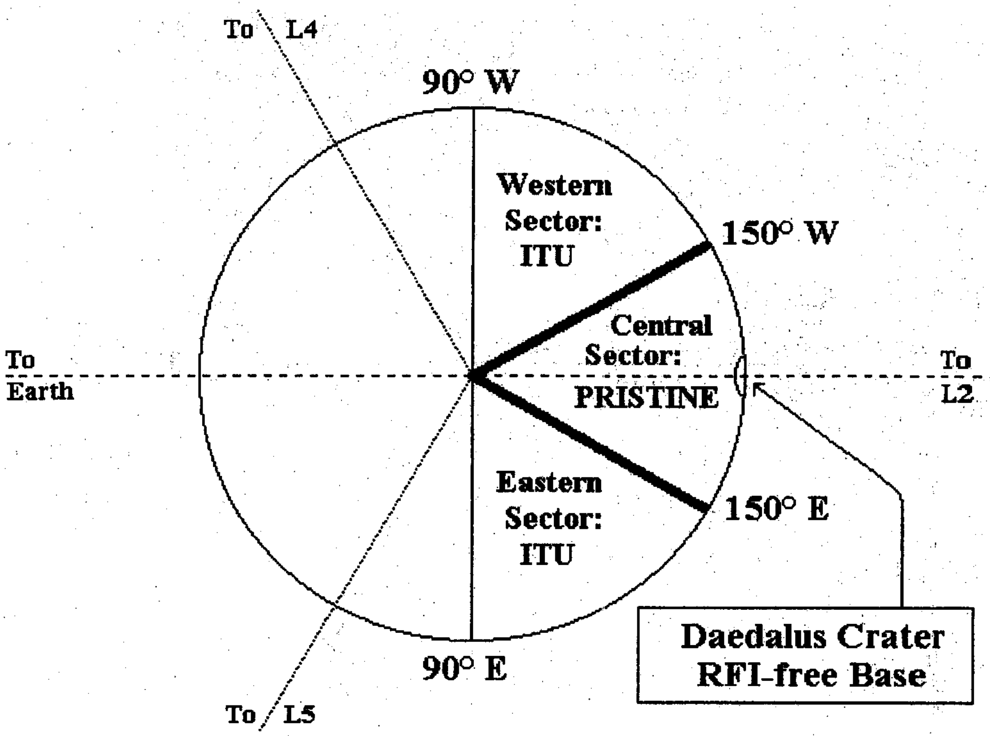

Fig. 11. This author's vision of the Moon farside with the Daedalus crater for SETI and radioastronomy.

its "pristine" radio environment totally free from man-made RFI. This Sector is where crater Daedalus is, a ~100 km crater located in between 177°E and 179°W and around 5° of latitude South. At the moment, this author does not know how high is the circular rim surrounding Daedalus.

(c) The Western Sector, in between 90°W and 150°W, can be used for installation of radio devices, but only under the control of the International Telecommunications Union (ITU-regime).

Also:

(3) The Eastern Sector is exactly opposite to the direction of the Lagrangian point L4, and so the body of the Moon completely shields the Eastern Sector from RFI produced at L4. Thus, L4 is fully "colonizable".

(4) The Western Sector is exactly opposite to the direction of the Lagrangian point L5, and so the body of the Moon completely shields the Western Sector from RFI produced at L5. Thus, L5 is fully "colonizable" in this author's vision, whereas it was not so in Heidmann's vision. In other words, this author's vision achieves the full bilateral symmetry of the vision itself around the plane passing through the Earth–Moon axis and orthogonal to the Moon's orbital plane, where the Lagrangian points L4 and L5 are located.

(5) Of course, L2 is also not colonizable at all, since it faces crater Daedalus and is just about its zenith. Any RFI-producing device located at L2 would flood the whole of the farside, and must be ruled out. L2, however, is the only Lagrangian point to be kept free, out of the five located in the Earth–Moon system. And there is no need to do Planetary Defense from L2 since Planetary Defense can already be done from both L1 and L3, located each on one side of the Earth. Finally, L2 is not directly visible from the Earth since shielded by the Moon's body, what calls for letting L2 "be alone"!

Planetary Defence from the nearest four Lagrangian points and RFI-free Searches pursued from crater Daedalus on the farside of the Moon are finally shown in Fig. 12.

There is a drawback, though. This is coming from the further two Lagrangian points L1 and L2 of the Sun–Earth system, located along the Sun–Earth axis and outside the sphere of influence of the Earth, that has a radius of about 924,646 km in all directions around the Earth. Precisely, the Sun–Earth L1 point is located at a distance of 1496557.035 km from the Earth towards the Sun, and the L2 point at the (virtually identical) distance of 1496557.034 km from the Earth in the direction

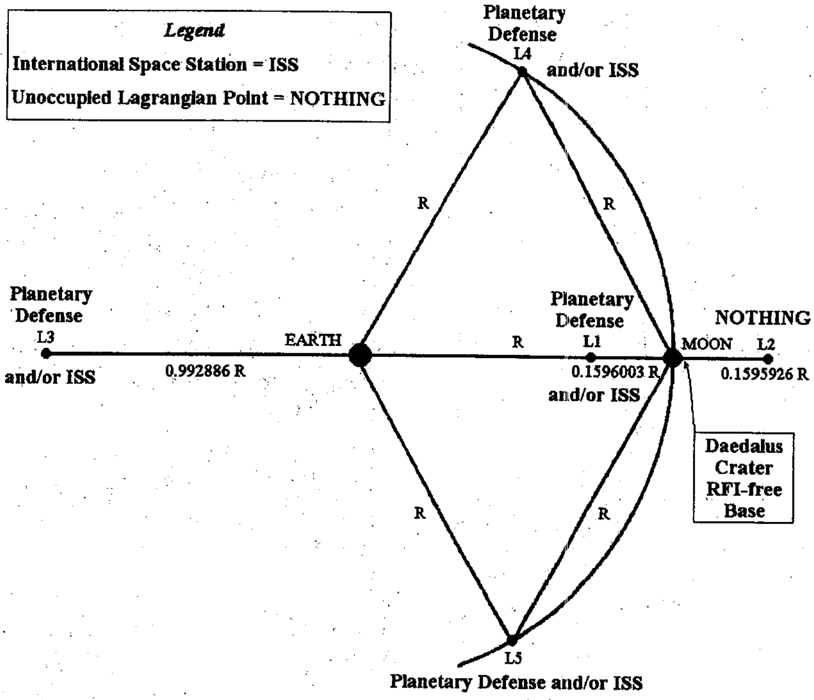

Fig. 12. This author's vision of the utilization of the Moon and of the Lagrangian points.

away from the Sun, that is toward the outer solar system. These two points have the nice property of moving around the Sun just at the same angular velocity as the Earth does while keeping nearly the same distance from the Earth at all times. Thus, they are ideal places for scientific satellites, and L1 has actually been utilized to this purpose since the NASA ISEE III spacecraft was launched on 12 August 1978 and reached the Sun–Earth L1 region in about a month. Later, another visitor to L1 was ESA's Soho spacecraft to explore the solar corona. As for the Sun–Earth L2 point, there are plans to let NASA's SIM (Space Interferometry Mission) be parked there, as will probably ESA's GAIA be as well. *So, all these satellites do "spoil" the otherwise RFI-free farside of the Moon when the farside is facing them.* But this does not happen all the time: every month, it lasts a forthnight, that is about half the time it takes to the Moon to make a full revolution around the Earth (synodic period = 29 days 12 h 44 min 3 s). This radio pollution of the Moon farside by scientific satellites located at the Lagrangian point L1 and L2 of the Sun–Earth system is unavoidable. We can only hope that telecommunications satellites will never be put there. As for the scientific satellites already there or on the way, it should be stressed that the radio frequencies they transmit are very well known, and this should help the Fourier transform of the spectral analyzers to be located on the Moon farside to get rid of them totally.

8. PROPOSING "RADIOMOON": A NEW SPACE MISSION TO SET UP AND OPERATE THE SPACE BASE IN CRATER DAEDALUS ROBOTICALLY

The selection of crater Daedalus instead of Saha solves the problem of pursing RFI-free Searches that will *never* (neither now nor in the future) *be hit by RFI from Earth-orbiting devices.*

However it will hardly be possible to link the base at crater Daedalus to other bases on the Moon visible side by virtue of optical fibers or landed data relays, because of the large distance of 2730 km existing between Daedalus and anywhere along the limb. To solve this problem, this author is now proposing a strategy completely different from all those proposed in the past to link Saha to the Earth.

The proposal put forward here is for a new space mission dubbed "RadioMoon" briefly described in this final section. RadioMoon is really made up by two spacecrafts: one lander and one orbiter. They fly together from the Earth to the Moon and are initially parked in a Moon circular and equatorial orbit having a radius of, say, 10,000 km. The orbital period of this single spacecraft around the Moon is 31.641 h (1.3 days). Then, at a time when the spacecraft is just crossing the Earth–Moon axis on the visible side, the lander is released from the orbiter and starts getting down towards the Moon surface along a Hohmann transfer half-elliptical trajectory, as shown in Fig. 13. By the very

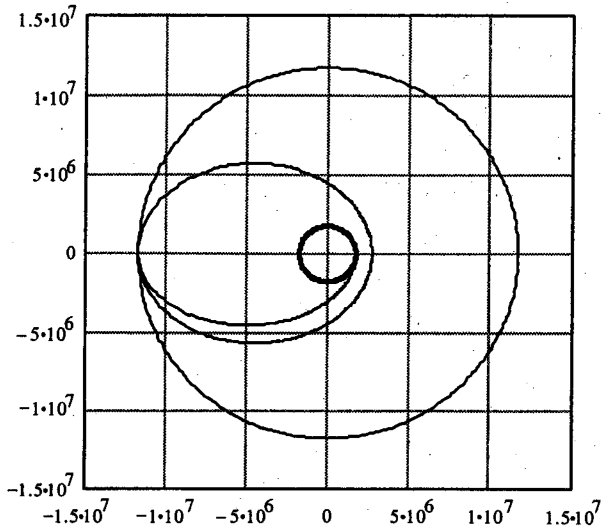

Fig. 13. Circling and Landing Orbits of the RadioMoon Mission to the Moon.

definition of this Hohmann transfer, the lander lands just at the longitude of 180°E, namely inside crater Daedalus (there could be slightly different manoeuvers to slow down the impact, of course, but the basic geometry of the Hohmann transfer keeps the same: semi-major axis 6378 km, eccentricity 0.742, time to get down from 10,000 km along the half-ellipse 6 h 52.86 min). The lander would be protected by airbags against impact damage: if it worked on July 4, 1997, for Mars Pathfinder, we can hardly figure out why it should not work for the Moon, where the gravity is less than a half that of Mars. Finally, the lander deploys a flat phased array, that would steer the beam electronically.

But what about the orbiter?

The orbiter's task is to gather data from the phased array at crater Daedalus when flying above the farside, and transmit these data back to the Earth when flying above the near side. And the other way round for giving the Earth's instructions to the phased array at Daedalus. This is by far the cheaper, easier and safer way to operate a Moon farside base from any astronautical point of view.

9. CONCLUSION

A unified vision of both the Earth's defense against dangerous asteroids and comets (Planetary Defense) and of the possible RFI-free searches to be conducted from the farside of the Moon has been presented.

Planetary Defense can be pursued from any of the four Lagrangian points nearest to the Earth, namely, in increasing distance, L1, L3, L4 and L5. It is suggested, however, that the use of confocal trajectories for missiles launched from L3 and L1 would ensure the optimal deflection of the dangerous asteroids or comets. An International Space Station or other spacecrafts could also be located at L1, L3, L4 and L5 in the future.

The Lagrangian point L2 has to be kept totally free from spacecrafts to ensure that RFI-free searches from the farside of the Moon become feasible. Since man-made RFI is increasingly blinding the sensitive radioastronomy instruments on the surface of the Earth, conducting RFI-free searches from the farside of the Moon appears to be the only reliable way to keep radioastronomy alive in the coming decades. Crater Daedalus at 180° of longitude E on the Moon farside emerges as the safest location to establish a base also for SETI, the Search of ExtraTerrestrial Intelligence. A space mission dubbed "RadioMoon" to operate this base in crater Daedalus has been outlined.

In conclusion, both Planetary Defense and Protection of the Moon Farside from human exploitation might well be called "ecological", inasmuch as they aim at keeping both the Earth and Moon environments just as fairly uncontaminated as they still appear to be at the beginning of the new century.

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