Deep Space Flight and Communications

Exploiting the Sun as a Gravitational Lens

Claudio Maccone

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Dr Claudio Maccone
International Academy of Astronautics & Istituto Nazionale di Astrofisica
Via Martorelli 43 - 10155 Torino (Turin)
Italy
Email: clmaccon@libero.it

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Contents

Preface

This is a book about unmanned space missions to the edge of the Solar System. And possibly beyond.

Readers may wish to read first the ''Brief Overview'' of the scientific and technical problems discussed in this book that is found on pp. xxxi–xxxiv hereafter.

Also, readers might wish to request the DVD of the Lecture that the author gave at NASA–JPL on August 18th, 1999, about ''The Sun's Gravity Lens and Its Use for Interstellar Exploration'' (running time: about 80 minutes).

This DVD may be requested by email to the author:

Dr. Claudio Maccone, email: *clmaccon@libero.it*

or, in the author's absence, to either of the following co-workers of his:

(1) Dr. Luca Derosa, email: *spacecraft@libero.it*
(2) Dr. Nicolo' Antonietti, email: *n.antonietti@libero.it*.

The present book is the result of merging two previously published, smaller books by the author. The first, *The Sun as a Gravitational Lens: Proposed Space Missions*, corresponds to Part I, and the second, *Telecommunications, KLT and Relativity*, corresponds to Part II of this revised and updated book.

If NASA and ESA decide to fund the first ''precursor interstellar mission'' to 550 AU or even beyond to 1000 AU in the decades to come, the goal of this book will have been reached.

Claudio Maccone
Torino (Turin), Italy, January 23rd, 2009

Preface to earlier works

I first met Frank Drake in 1987 at Balatonfüred, Hungary, at the *Second International Conference on Bioastronomy* (officially called the 99th Colloquium of the International Astronomical Union, held June 22–27, 1987). Bioastronomy is the newly born branch of science trying to assess whether life exists elsewhere than on Earth. As far as we know, life can come in a variety of forms, either less or more biologically advanced than humans are at present. Next to the very primitive forms of life that biologists are currently trying to detect (e.g., on Mars), it is quite reasonable to admit that civilizations more advanced than ours possibly exist in the Galaxy also. If this is the case, one may try to detect them by using the several large radiotelescopes now available on Earth to pick up the possible "leakage" of radio signals emitted from planets orbiting other nearby stars, just as the Earth is constantly emitting a large quantity of radio waves that have been outflowing into space since humans discovered the technology of radio transmission about 1900 AD.

Frank Drake was the first scientist to try detecting, back in 1960, whether "intelligent" radio signals were being emitted by planets around two nearby Sun-like stars (ε *Eridani* and τ *Ceti*). This was *Project Ozma*, and it marked the beginning of *SETI*, the (radio) *Search for Extra-Terrestrial Intelligence* that has been continuing ever since in some of the most technologically advanced countries, like the U.S.A., Russia, France, Italy, Japan, Australia, and Argentina.

At the Balatonfüred 1987 conference Frank Drake gave a talk titled *Stars as Gravitational Lenses* that greatly impressed me. He described the huge magnification (i.e., the very intense focusing) that the gravitational field of the Sun would have on the radio waves (or light rays) originating, for instance, at the Galactic center, and then traveling unaltered through the vast Galactic distances until they graze the Sun's surface. These rays are then deflected by the Sun's gravity and made to focus along a line starting at 550 AU from the Sun. If one could construct a spacecraft capable of traveling 550 AU (and beyond, perhaps to 1,000 AU), the spacecraft could transmit back to Earth the greatly magnified radio picture of whatever lies at great distances in the opposite direction to the Sun. I have dubbed both the spacecraft and the entire space mission *FOCAL*.

In the years 1987–1992 I made a personal preliminary study of the FOCAL space mission which made clear to me the five basic points listed below. Meanwhile, my discussions with scientists and engineers, experts in areas of importance to the FOCAL space mission, led me to organize the first one-day international conference on FOCAL. This was the *Space Missions and Astrodynamics I* conference held at Politecnico di Torino (the Engineering School in my home city of Turin, Italy) on June 18, 1992. I later edited the proceedings of this conference and published them in two issues of the *Journal of the British Interplanetary Society* (February and November 1994). By that time interest in FOCAL by various scientists and engineers had grown to such an extent that the time was ripe to submit a formal proposal for the mission to one leading space agency. Opportunity was taken of the *Call for New Mission Ideas* (M3) issued by *ESA*, the *European Space Agency*, early in 1993. So on behalf of a large group of scientists and engineers from both Europe and the U.S.A., on May 20, 1993, I submitted the 50-page FOCAL proposal to ESA, who later included it as Proposal #24 among the Responses to the Call for Mission Concepts for the *Horizon 2000 Plus* plan (see ESA SP-1180, August 1995, p. 115, #24). It was then wittily remarked by the French professor Roger Bonnet, Director of Scientific Programs of ESA, that had FOCAL been approved by the Agency, it would have provided work not just for the present generation of ESA employees, but also for the generations of their sons and grandsons.

This remark by Bonnet obviously pointed out the tremendous amount of work necessary to put up a very deep space mission like FOCAL. However, it could hardly deter far-sighted scientists and engineers from thinking about such a deep space mission. I proceeded to promote the FOCAL mission when I ran the *Space Missions and Astrodynamics II and III Conferences* at the Politecnico in Turin in October 1994 and June 1995, respectively. At the *International Astronautical Federation Congress* in Oslo, October of 1995, the *International Academy of Astronautics* (*IAA*) agreed to hold the *First IAA Symposium on Missions to the Outer Solar System and Beyond* at the Politecnico in Turin on June 25–27, 1996. Some 50 experts from NASA-JPL, Russia, and European countries gathered to discuss the perspectives of future exploration of the outer solar system, and there FOCAL gained ground as the "must" mission before any attempt to go beyond 1,000 AU from the Sun was even conceived.

Now the five basic points summarizing the importance of the FOCAL space mission are as follows:

(1) FOCAL would necessarily be the *first precursor interstellar mission of humankind*. In fact, the minimal distance of 550 AU is about 14 times the distance from the Sun to Pluto, and so FOCAL would, by far, surpass any other ongoing "deep space" mission (such as *Voyagers 1* and *2*, *Pioneer 10* and *11*) or planned (the NASA-JPL *Pluto Express*). Put in better terms still, one might say that any future interstellar mission of humankind will necessarily be a FOCAL mission also, since beyond 550 AU the Sun will *always* be serving as a lens for *some* direction.

(2) Reaching 550 AU takes a long time. How long this flight time might be depends on the propulsion system adopted (possibly nuclear-electric propulsion, solar sailing, magnetic sailing, or a combination of all of them). One can currently imagine this flight taking between 10 and 50 years. It is true that one does *not* have to stop FOCAL at just 550 AU, because *every* point along the straight-line trajectory beyond 550 AU *still is* a focal point. This paves the way to an even more ambitious mission, up to 800 or 1,000 AU, requiring yet more time. One such mission studied at JPL in the 1980s has the name *TAU* (*Thousand Astronomical Units*). It would yield such a wealth of scientific results through the study of parallaxes of stars, the heliosphere[1] and the heliopause,[2] the interstellar medium, and the possible detection of gravitational waves, that the FOCAL (or TAU) mission would be justified independent of the gravitational focusing effect.

(3) Which members of the scientific and technological community would be interested in the results provided by FOCAL? First, astrophysicists would enjoy getting a detailed radio picture of the Galactic center, where a massive black hole is suspected to exist and stars are so close that unexpected physical phenomena could be revealed. This high-resolution radio picture can be obtained only by using the Sun as a gravitational lens jointly with a spacecraft capable of observing on the hydrogen line (1,420 MHz) and/or similar frequencies (1.6 GHz for the OH maser; 22 GHz for the water maser, and so forth). Second, a spacecraft crossing the Kuiper Belt would provide planetary scientists with a wonderful opportunity to investigate the lesser bodies recently discovered to orbit the Sun roughly between 40 AU and 100 AU. Other important fields of investigations, such as plasma physics of the heliosphere and heliopause, determination of parallaxes of stars, perturbation of orbits leading to the possible discovery of new bodies, have already been mentioned. So let me just add that, last but by no means least, space engineers and technologists would have to overcome challenges like the selection of the best propulsion system to get there, how to keep track of the spacecraft at such unprecedented distances, and how to optimally compress information to enable the huge data flow from the FOCAL spacecraft back to the Earth. Advanced technology corporations would support the approval of FOCAL by space agencies as a proving ground for improving technology already in existence.

(4) SETI deserves a separate discussion. As Frank Drake said in 1987, only by exploiting the gravitational lens of the Sun can we expect to detect signals that are extremely weak because they come from so far away in the Galaxy. Consider the former NASA *SETI Targeted Search* (ended abruptly in October 1993 by the U.S. Congress on the ground of "necessary budget cuts"). The goal of this project was to observe 773 Sun-like stars with the highest possible sensitivity

[1] The *heliosphere* is the region surrounding the solar system where the solar wind dominates the interstellar plasma. Despite the word "sphere" as part of the name, the region is not spherical, but extends roughly 150 AU in front, and much farther behind.

[2] The *heliopause* is the imaginary surface bounding the heliosphere.

provided by the collecting area of the largest radiotelescopes on Earth (i.e., the Arecibo telescope located in Puerto Rico, the Goldstone 70-meter Deep Space Network antenna in the Mojave desert of California, the Nançay radiotelescope in France, the Parkes antenna in Australia, etc.). Because of the limited collecting area of these telescopes, the distance of the target stars could not exceed 100 light years. But this distance is very small compared with the size of the Galaxy (100,000 lt-yr in diameter), so even if the NASA-SETI project had been funded, the part of the Galaxy explored for extraterrestrial life would have been very small. In other words, the problem is that the collecting area of radiotelescopes on Earth cannot exceed the current values by much, and hence one cannot detect even weaker signals. One might say that the generation of SETI scientists of the school of Frank Drake in the U.S.A., of Nikolai Kardashev in Russia, and of Jean Heidmann in France, have already done the best they can do on the suface of Earth. It is now up to the space scientists to take the lead in SETI by putting up the first FOCAL space mission. FOCAL could detect signals 2 to 3 orders of magnitude weaker than signals detectable on Earth, and could thus enable the detection of civilizations located much farther out, around the Galactic center 32,000 lt-yr away, or even farther, thus increasing dramatically the probability of humankind's first contact with ET.

(5) Politicians of the highest caliber might also be interested in supporting an epoch-making space mission like FOCAL for their own personal prestige. In fact, the *costs* of the first precursor interstellar mission of humankind could hardly be supported by a single national space agency, and international cooperation would be necessary. The U.S. and NASA could, at a minimum, provide the JPL and Deep Space Network expertise, the Russians could provide the launcher, the Europeans could be in charge of the scientific payload, as could the Japanese, etc. Finally, the members of the United Nations could give their patronage to a space mission of unsurpassed "grandeur" as FOCAL, symbol of the first expansion of humankind outside the solar system.

Claudio Maccone
Secretary of the Interstellar Space Exploration Committee and
Member of the SETI Committee,
International Academy of Astronautics

Acknowledgments

As a member of two committees of the International Academy of Astronautics—the SETI Committee and the Interstellar Space Exploration Committee—I am greatly indebted to my fellow members for many helpful discussions as well as for encouragement to publish this book.

Within the SETI international community I had the honor and privilege of discussing the gravitational lens of the Sun with the late, incomparable Carl Sagan as well as with the initiator of experimental SETI, Frank Drake. In Russia, Nikolai Kardashev gave me the opportunity to present my views on the FOCAL space mission at the Sternberg Astronomical Institute in Moscow in October 1996. To these three outstanding scientists I would like to express my deepest feelings of gratitude. SETI Institute scientists and engineers also taught me a great deal: Jill Tarter, Kent Cullers, Seth Shostak, Tom Pierson, and many others served as my teachers of experimental SETI, while Laurance Doyle and others did the same on the subject of habitable zones and extrasolar planet searching. John Billingham, former SETI Chief at NASA-Ames and Coordinator of the IAA SETI Committee, has always encouraged my SETI-related research, from FOCAL to the intended Moon farside radiotelescope, and to the "crazy" topic of "SETI via Wormholes". In Europe, inspiring personalities have been Jean Heidmann in France and Ivan Almar in Hungary, both of whom also attended and provided outstanding contributions at the conferences I ran in Turin. May I also add the names of François Biraud in France and Robert S. Dixon at the Ohio State University, who independently foresaw back in 1983, as I did, that SETI could be greatly improved by the replacement of the Fast Fourier Transform by the *Karhunen–Loève Transform* (KLT). Finally, I am happy to acknowledge the contribution of the outstanding SETI work of Stuart Bowyer and Dan Werthimer at UC Berkeley, of Paul Shuch in New York, of the only master of experimental SETI in Italy, Stelio Montebugnoli of the CNR Radio Astronomy Institute in Bologna, and of Cristiano Cosmovici of the CNR in Rome.

The other IAA Committee of which I am part is the Interstellar Space Exploration Committee, created back in 1984 by the leading British physicist Leslie Shepherd. To him, as well as to the present coordinator, Giovanni Vulpetti of Telespazio in Rome, I am indebted for many inspiring conversations about interstellar flight, including relativistic flights. In particular, I must here mention Giovanni's outstanding discovery (1992–1995) of a Sun flyby by virtue of a solar sail that would literally throw the solar sail out of the solar system at a much higher speed than previously believed. If the FOCAL spacecraft was to be a solar sail, it might reach 550 AU in 25 to 30 years. Solar sails also are the leading field of expertise of one more Committee member, Gregory Matloff of NYU, to whom I am very grateful for suggestions, friendship, and hospitality. Another member of the Committee to whom I am very grateful for his great cooperation is Macgregor S. Reid, Technical Executive Assistant to the Director of JPL, who hosted me at JPL several times and put me in touch with many outstanding experts working there. One of these is Rob Stahle, the *Pluto Express* program manager, who obviously faces problems that are very much akin to those of the FOCAL mission.

The organization of the above-mentioned conferences in my home town of Turin would not have been possible without the decisive support of Giancarlo Genta, former director of the Mechanical Department at the Politecnico and now president of the G. Colombo Center for Astrodynamics. Similarly, the organization of a *SETI-Day* on June 28, 1996, at the Academy of Sciences of Turin, was greatly helped by another friend, Danilo Noventa of the Peace Watch Committee in Turin. Special thanks are due to Salvatore Santoli of the Rome Branch of INT (International Nanobiological Testbed), editor of the Exobiology Section of the *Journal of the British Interplanetary Society* and leading nanotechnology expert, for his constant, friendly, and wonderful cooperation. Also my former student, Michele Piantà, shared with me interest in the study of the FOCAL space mission and greatly helped me with the preparation of the tables and drawings that are contained in this book.

Turning now to the publication of the book, I would like to stress my particular gratitude to Prof. Richard A. Blade of the University of Colorado at Colorado Springs for his hospitality, for understanding the importance of the FOCAL space mission, and for editing and supporting the publication of this book by Springer-Praxis.

The author wishes to thank his Publisher, Clive Horwood, and Dr. John Mason, Chief Subject Advisory Editor of Praxis, for agreeing to publish this book which combines his two previous, smaller books (corresponding to Part I and Part II of this upgraded book). The author also wishes to thank Neil Shuttlewood of OPS Ltd. for re-setting the equations, certainly not an easy task.

And, of course, I am indebted to Alenia Aerospazio (Divisione Spazio), the space company where I have been employed since 1985, for the opportunity to do research.

Finally, I want to thank my parents, whose loving efforts, despite their modest financial means, encouraged and supported my studies over many years.

Claudio Maccone
Torino (Turin), Italy, August 24, 1997

Foreword

Wherever in space there are intelligent creatures like us, they will be driven to explore and understand our Universe, just as we do. We and they wish to glimpse the farthest depths of space with the greatest clarity allowed by the laws of nature. To this end, we build, at great expense, ever more powerful telescopes of all kinds on Earth, and now in space. As each civilization becomes more knowledgeable they will recognize, as we now have recognized, that they have been given a single great gift: a lens of such power that no reasonable technology could ever duplicate or surpass its power. This lens is civilization's star: in our case, the Sun. The gravity of each such star acts to bend space, and thus the paths of any wave or particle, in the end creating an image, just as familiar lenses do.

This lens can produce images which would take perhaps thousands of conventional telescopes to produce. It can produce images of the finest detail of distant stars and galaxies. Every civilization will discover this eventually, and surely will make the exploitation of such a lens a very high priority enterprise. One wonders how many such lenses are being used at this moment in time to scan the Universe, capturing a flood of information about both the physical and biological realities of our time.

We are just beginning to appreciate the power of such a lens, and to contemplate its exploitation. In this book is written the theory and potential performance of such a lens, not only for light and radio waves, but even for gravitational waves and neutrinos. But such a lens can only be utilized if a major challenge is met. This challenge derives from the fact that the magnificent images created by the lens for any electromagnetic waves, including light and radio, are formed at a distance of at least 550 AU from the Sun. Thus, at this very moment images of fantastic clarity and brightness are being created far out in space. The challenge to us is to send adequate detectors to these great distances to capture those images.

In this book Claudio Maccone describes this technological challenge, and how it might be met by the FOCAL mission. He points out that there are many scientific bonanzas in addition to the gravitational lens which will accrue from such a mission.

Here can be found the detailed technical requirements of the mission, as well as firm and accurate quantitative values for the imaging abilities of the lens.

This is a technical primer for what, in the long run, may be the most important space mission we will conduct. Readers of this book should wonder, as they read, how many times this same text has been created over the eons on the planets of other stars, and how many stars already are serving as the super-powerful eyes of the creatures of distant planets.

Frank D. Drake
Professor of Astronomy and Astrophysics
and Former Dean, Division of Natural Sciences,
University of California, Santa Cruz

Figures

Tables

Abbreviations and acronyms

AC	Aurora Collaboration
AOCS	Attitude and Orbit Control System
ASS	All-Sky Survey
AXAF	Advanced X-ray Astrophysics Facility
BAM	Bordered Autocorrelation Method
BETA 2	Software program
BPPP	Breakthrough Propulsion Physics Program
CBR	Cosmic Background Radiation
CMB	Cosmic Microwave Background
CMR	Cosmic Microwave Radiation
CNR	Consiglio Nazionale delle Ricerche
COBE	COsmic Background Explorer
DAstCom	Data on Asteroids and Comets
DBS	Direct Broadcast Satellite
EHOF	Extended Heliocentric Orbital Frame
ESA	European Space Agency
ET	ExtraTerrestrial
FFT	Fast Fourier Transform
FOCAL	Space mission
FT	Fourier Transform
GRO	Black holes within the Milky Way
HAE	High-Amplification Event
HIF	Heliocentric Inertial Frame
HPBW	Half-Power Beam Width
HR	Hertzsprung–Russell diagram
HST	Hubble Space Telescope
IAA	International Academy of Astronautics
INT	International Nanobiological Testbed

IR	InfraRed
IRAS	InfraRed Astronomical Satellite
ISP	InterStellar Probe
ISP STDT	ISP Science and Technology Definition Team
JBIS	*Journal of the British Interplanetary Society*
JPL	Jet Populsion Laboratory
KL	Karhunen–Loève
KLT	Karhunen–Loève Transform
LDR	LIGO Data Replicator
LMC	Large Magellanic Cloud
MAnE	Mission Analysis Environment
META	Project
MHD	MagnetoHydroDynamic
NASA	National Aeronautics and Space Administration
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
NYU	New York University
PCA	Principal Components Analysis
PL	Period–Luminosity
PLL	Phase Locked Loop
RA	Right Ascension
SETI	Search for ExtraTerrestrial Intelligence
SETISAIL	Solar Sail space mission for SETI
SETV	Search for ExtraTerrestrial Visitation
SGF	Solar Gravitational Focus
SIM	Space Interferometry Mission
SIRTF	Space InfraRed Telescope Facility (Spitzer Space Telescope)
SMC	Small Magellanic Cloud
STAIF	Space Technology and Applications International Forum
SVD	Singular Value Decomposition
TAU	Thousand Astronomical Units (space mission)
TF	Tully–Fisher (relation)
UV	UltraViolet
VLBI	Very Large Baseline Interferometry
ZAMS	Zero Age Main Sequence

A brief overview of the Sun as a gravitational lens

Two foci of the gravitational lens of the Sun are predicted to exist by the general theory of relativity (see Figure 1).

(1) *A focus for electromagnetic waves*, located along a line starting at a distance of 550 AU (Astronomical Units)—that is, 3.17 light days, or 14 times the distance from the Sun to Pluto. It will be proved that any point beyond this minimal distance is a focus also. Thus, any spacecraft that can fly to 550 AU and beyond can take full advantage of the huge radio magnifications of any astronomical object lying on the other side of the Sun with respect to the spacecraft position.

(2) *A focus for gravitational waves and neutrinos*, located within the solar system at distances 22.45 AU and 29.59 AU (roughly between the distances of the orbits of Uranus and Neptune). The physical justification for the existence of this focus is that

   (a) a gravitational wave can *penetrate* through the Sun because such waves scatter significantly only in the presence of significant mass density rather than the charge on electrons which scatter electromagnetic waves; and

   (b) the bulk of the Sun's mass is more highly concentrated within its inner layers than within its outer layers (i.e., the Sun's radial density is maximum at the center and zero at the surface).

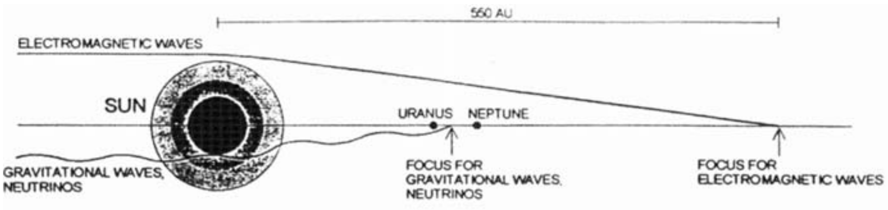

Figure 1. Comparison between the paths of electromagnetic waves and gravitational waves being focused by the gravitational field of the Sun.

THE PROPOSED FOCAL SPACE MISSION TO 550 AU AND BEYOND TO 1,000 AU

Part I of this book is devoted to studying the *FOCAL space mission*. By this we mean to let a spacecraft travel to 550 AU and beyond until it can detect the greatly magnified radio pictures of any radio source located on the other side of the Sun with respect to the spacecraft position.

In this book no study will be made of space missions intended to detect the gravitational waves focused by the Sun, since these missions were studied by David Sonnabend of JPL in 1979 (see [1]).

Part I opens with a review of the gravitational lens of the Sun based on Einstein's general relativity (Chapter 1). This is the so-called ''naked'' lens, namely the purely convergent lens due to gravity only (i.e., no Coronal effects are taken into account). It is then shown that

(1) The naked Sun's focus lies on a focal sphere of about 550 AU in radius.
(2) The gain (= magnification) of such a gravitational lens is huge: about 57 dB at the hydrogen line frequency of 1,420 MHz, and similarly for other frequencies of radioastronomical interest.
(3) The FOCAL spacecraft position must be very tightly ($\sim$100 km) aligned with the source of electromagnetic waves and the Sun center.

Chapter 2 summarizes the cruise science that could be profitably done by the FOCAL spacecraft while *en route* to 550 AU and beyond. The implications for cosmology (re-calibration of the size of the Universe), for nuclear processes associated with cosmogony, and for stellar parallaxes computation would be profound.

The FOCAL direction of exit out of the solar system is determined by which nearby star we wish to see magnified. In Chapter 3, we compute such a direction, as well as the relevant Sun flyby characteristics, for the nearest 50 stars. And in Chapter 4 we show that a time-optimized design of the spacecraft trajectory to reach a distance of 550 AU is vital for success. This is no simple task, however, since it must be achieved by either conventional chemical engines, and/or by nuclear-electric propulsion and/or by solar sailing (see [2]). Each propulsion system has its own advantages.

NEW TOPICS: GL-SETI, THE SOLAR CORONA EFFECTS "PUSHING" THE FOCUS FARTHER OUT, AND FOCUSED POWER PROPULSION

Part I of this book continues with five further chapters summarized hereafter.

(1) The newly re-written Chapter 6 deals with the use of the gravitational lenses of nearby stars to get magnified radio pictures of objects emitting electromagnetic waves from much beyond the nearby lensing stars. This effect could be used for either astrophysical investigations and for SETI. When used for SETI, it originates a new kind of SETI search, called ''GL-SETI'' (an acronym for

"Gravitational Lensing SETI"), in addition to the two traditional approaches of the SETI "targeted search" and "all-sky survey", as described by the SETI League President, Richard Factor, in Sections 6.2 and 6.3. His introduction is just qualitative, however. A more profound, mathematical investigation of GL-SETI reveals the diffficulties of probing this new research field, as shown in Section 6.4 by the new equation found by the author to relate the magnification of the lensing star, the distance of the ET transmitter, and the power of the ET transmitter. Finally, in Section 6.5 another application of GL-SETI is provided in case SETV, the Search for Extra-Terrestrial Visitation (within the solar system) is proved in the future to be real science, rather than pure science fiction.

(2) In Chapter 7 the first investigation (to the best of our knowledge) is presented about the gravitational lenses of the four nearest stars to the Sun in the Galaxy: Alpha Centauri A, B, C (Proxima), and Barnard's star. This mathematical description is intended to lead to a future, full description of the "radio bridge" between each one of these stars and the Sun, obtained by exploiting the gravitational lenses of all of them. These results show the enormous gains and energy savings that would affect the telecommunication link between the Sun and each one of these stars, were both gravitational lenses used at the same time. And this might indeed be used in the future in case human probes were able to reach, say, Alpha Centauri, and needed to keep their radio link with the Earth.

(3) In Chapter 8 is given the rather difficult mathematical theory of the Solar Corona effects on radio waves grazing the surface of the Sun. We start from the well-known Baumbach–Allen model of the Corona and then go over to finding the actual minimal focal distances by taking into account the frequency of the grazing waves. The result is that the action of the Corona counterbalances and even wins over the action of gravity by "pushing out" the actual minimal focal distance beyond 550 AU. This is "unfortunate" from the point of view of planning space missions intended to reach the actual focuses of the gravitational lens of the Sun, but is much more realistic than naively hoping for a focus at 550 AU, just as if there was no Corona around the Sun!

(4) The mathematical theory of the Corona given in Chapter 8 is then applied in Chapter 9 to the very special case of the Cosmic Microwave Background (CMB), whose Planck spectrum has its peak frequency at 160.378 GHz. For this frequency, we show that the Sun's minimal focal distance is 763 AU because of the Corona effects, rather than just 550 AU. We also point out that the NASA Interstellar Probe (ISP), currently under study at JPL and expected to be launched in 2010 in the direction of the incoming interstellar wind, would reach 763 AU around 2057. ISP could thus prove for the first time the physical existence of the Sun's gravity lens if suitably equipped with a photometer or a bolometer tuned to 160 GHz.

(5) Finally, an entirely new possibility, using the Sun's gravitational lens for propelling a spacecraft over to interstellar distances, is explored in Appendix E. Although we had to confine our description to the basic ideas only (i.e., without equations), this possibility could one day prove vital to help human expansion

into space up to the nearest stars and perhaps beyond. This exploitation of the Sun's gravity lens might possibly be achieved in either of two ways.

(a) exploiting the gravitational focusing of other stars on synthetic solar sails; or
(b) placing a solar power station on the opposite side of the Sun at distances higher than 550 AU and then moving it slowly toward the Sun. In this case, the minimal focal distance of the Sun's lens would be pushed farther and farther out, and so would be the sail located at its minimal focal distance. This second technique has one great advantage over the first one: it would work in all directions out from the Sun center, thus enabling a really free selection of the destination stars.

In conclusion, this book offers an even more comprehensive vision of the phenomenon of the Sun's gravity lens, now extended to the gravitational lenses of the nearest four stars in the Galaxy.

The author is convinced that the new, grand goal of humankind in the new millennium will be the exploration of our Galactic neighborhood and its human settlement. Hopefully, this book will be of use to future generations of space scientists and engineers willing to exploit the Sun's gravity lens and its unusual properties for applications to interstellar flight and to the scientific exploration of the Galaxy.

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