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MISSIONI SPAZIALI PER SFRUTTARE IL SOLE COME LENTE GRAVITAZIONALE

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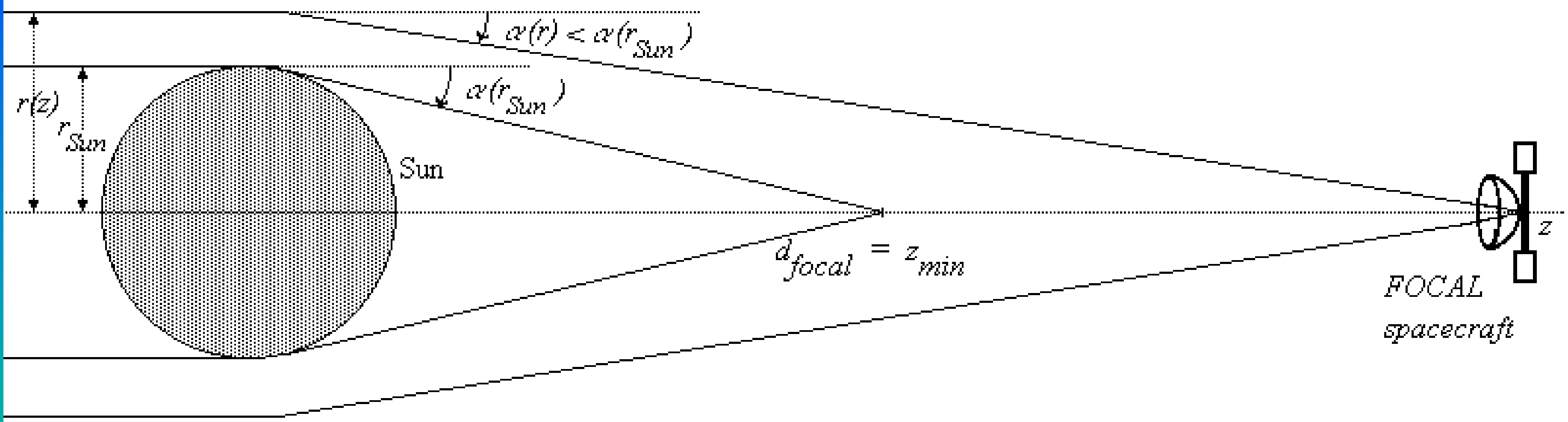
Gravitational Lens of the Sun



Geometry of the gravitational lens of the Sun: minimal focal length at 550 AU and FOCAL spacecraft position.

Gravitational Lens of the Sun

- The geometry of the Sun gravitational lens is easily described: incoming electromagnetic waves (arriving, for instance, from the center of the Galaxy) pass *outside* the Sun and pass within a certain distance *r* of its center.
- Then a basic result following from General Relativity shows that the corresponding *deflection angle (r)* at the distance *r* from the Sun center is given by (Albert Einstein, 1915):

$$\alpha(r) = \frac{4GM_{Sun}}{c^2 r}.$$

Gravitational Lens of the Sun

- Let's set the following parameters for the Sun:
  1. Mass of the Sun: $1.9889164628 \cdot 10^{30}$ kg, that is μSun = 132712439900 kg^3s^{-2}
  2. Radius of the Sun: 696000 km
  3. Sun Mean Density: 1408.316 kgm^{-3}
  4. Schwarzschild radius of the Sun: 2.953 km

  One then finds the BASIC RESULT:

MINIMAL FOCAL DISTANCE OF THE SUN:

548.230 AU ~ 3.17 light days ~

13.86 times the Sun-to-Pluto distance.

BOOK by Claudio Maccone

Infinity of Focuses > 550 AU

- There is an infinity of focuses from 550 AU outward in any direction. Thus, 550 AU is actually the minimal focal sphere.
- In the practice, we won’t have to stop a spacecraft just at 550 AU, but we just let it go.
- The further the spacecraft goes beyond 550 AU, the better it is. In fact, radio waves impinging on the spacecraft at distances higher than 550 AU will have to cross less and less dense layers of the Solar Corona.
- The Solar Corona is difficult to model. Essentially, because of the radially decreasing electron density, the Solar Corona acts as a divergent lens opposing the convergent lens of gravity.
- We shall study the Corona later. Just the Naked Sun for now.

Gain of Any Star as a Lens

- The "gravity lens" concept means that the Sun (and any other massive celestial body) is an antenna since it can increase the intensity of the signal, by virtue of its deflection.

- We define the Gain associated to any star, G_{star}, as the ratio between the intensity of the signal in presence of the star compared to the intensity of the signal without the star. It can be proven that, along the focal axis, one has

$$G_{star}(\lambda) = 4\,\pi^2\,\frac{r_g}{\lambda} = \frac{8\,\pi^2\,G\,M_{star}}{c^2}\cdot\frac{1}{\lambda}$$

The gain is constant along the focal axis but is wavelength-dependent. There, r_g is the Schwarzschild radius of the star.

Sun Gain at Some Frequencies

- In the following table we remind on-axis GAIN of the gravitational lens of the naked Sun lens for seven important frequencies:

Line	Neutral Hydrogen	OH maser	Water maser	Ka Band	CMB peak	**Visible red**	**Visible Violet**
Frequency **ν (GHz)**	1.420	1.6	22	32	160	**4.3 10^5**	**5.5 10^5**
Wavelength **λ (cm)**	21	18	1.35	0.937	0.106	**700 nano m**	**400 nano m**
Naked Sun Gain (dB)	**57.4**	**57.9**	**69.3**	**71.46**	**80.40**	**112.22**	**114.65**

Off-Axis Gain for any Star

- Off axis, when the spacecraft is at a distance ρ from the focal axis, and when it is at a distance z from the star, *the gain* can be proved to be:

$$G_{star}(\lambda, \rho, z) = 4\pi^2 \frac{r_g}{\lambda} \cdot J_0^2\left(\frac{2\pi\rho}{\lambda}\sqrt{\frac{2r_g}{z}}\right)$$

where $J_0(x)$ is the Bessel function of order zero and argument x

- The *total gain* for the combined (Star + receiving antenna) system is:

$$G_{Total}(\lambda) = G_{star}(\lambda) \cdot G_{antenna}(\lambda)$$

and so it increases with the CUBE of the frequency (next slide).

Total Gain of Star+Spacecraft

- If a spacecraft (S/C) has an antenna with radius $r_{antenna}$ and efficiency $k_{antenna}$, the spacecraft antenna gain is given by

$$G_{antenna}(\lambda) = 4\pi \frac{A_{physical} \cdot k_{antenna}}{\lambda^2} = \frac{4\pi^2 r_{antenna}^2 \cdot k_{antenna}}{\lambda^2}$$

and is proportional to the inverse of λ^2.

- The *total gain* for the combined (Star+S/C receiving antenna) system is proportional to the inverse of λ^3 and is:

$$G_{Total}(\lambda) = G_{star}(\lambda) \cdot G_{antenna}(\lambda) = \frac{32\pi^4 G M_{star} r_{antenna}^2 \cdot k_{antenna}}{\lambda^3}$$

Sun comes BEFORE interstellar!

- ***Sun's Focus Comes FIRST.***
- ***Interstellar Target Comes SECOND.***

1) The Sun's gravity focus is ***MUCH CLOSER*** than the target star, actually hundreds or thousand of times closer according to the target star (for α Cen it is 253 times closer than 1000 AU, where the "true" focus is found by taking the CORONA into account.
2) ***BEFORE*** any interstellar probe is launched towards a nearby star, we need a highly magnified radio-map of whatever lies around that star. And this can be achieved only by sending a probe to the opposite direction to let the Sun magnify!
3) It is much ***CHEAPER*** to reach 550 AU or 1000 AU than hundreds of AU, and it takes so much time less!

ASTRODYNAMICS: Max Speed

SOLAR SYSTEM EJECTION PROBLEM :

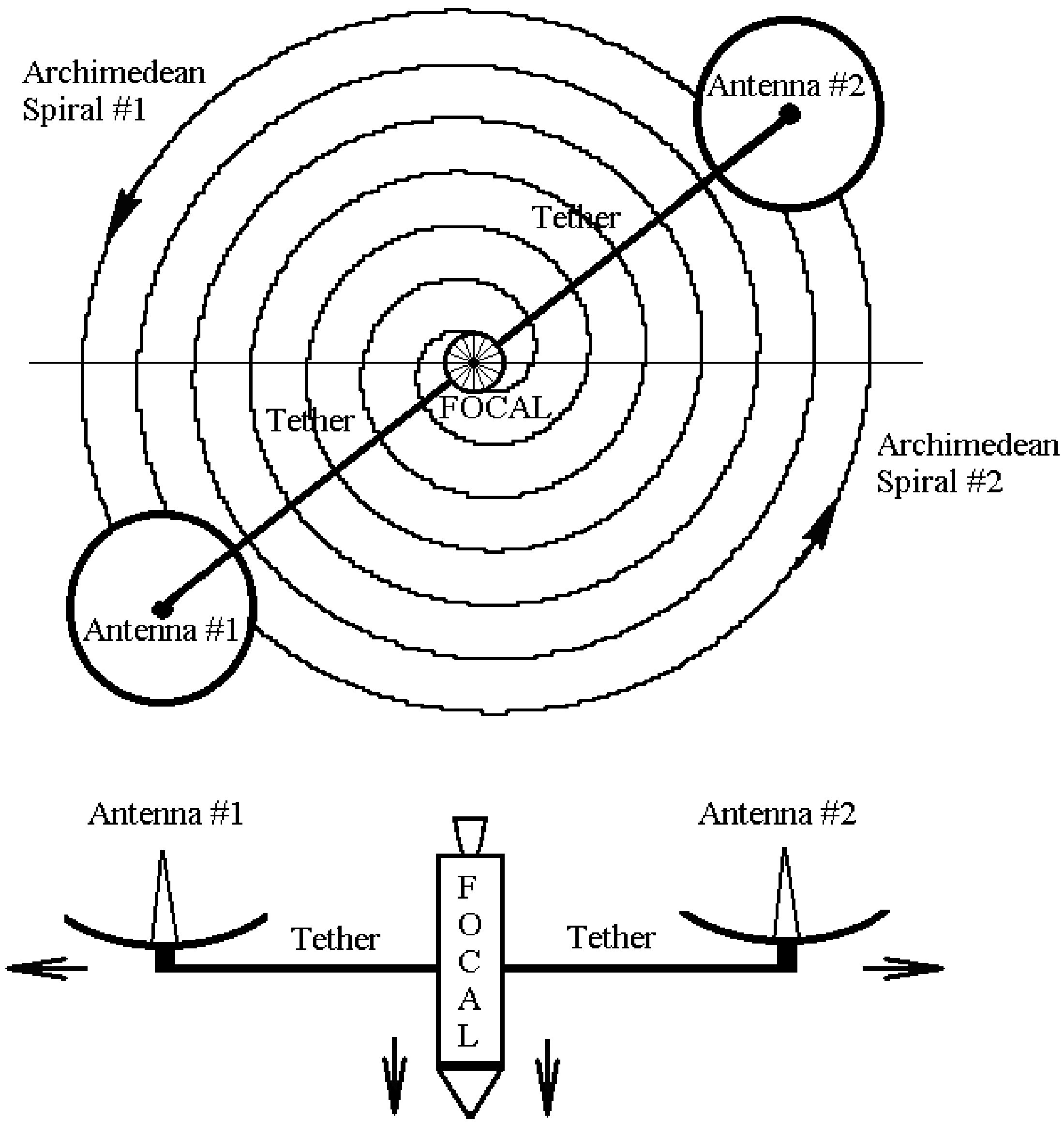
- ***Find the sequence of optimal FLYBYS within the solar system such that***
- ***THE SUN FLYBY IS THE LAST ONE and***
- ***the Focal probe LEAVES the solar system at the MAXIMUM POSSIBLE SPEED…***
- ***and in the direction OPPOSITE to the target star.***
- Conclusion: **ONE TARGET – ONE MISSION !!!**
- This problem was first considered by K. Ehricke in 1972. Today's Astrodynamics go for better solutions!

The Solar Corona

- So far, we have been concerned with the Naked Star Gravitational Lens, due to a spherical distribution of Mass.
- However, above the surface of the Sun, the Corona extends into space across distances that are comparable to the Sun radius, and the coronal effects may only complicate the physical picture of the Sun as a gravitational lens.
- How does the Sun Corona affect the electromagnetic waves convergence? How does the Sun Corona affect the electromagnetic waves gain?

TWO TETHERED ANTENNAS

INTERFEROMETRY in space

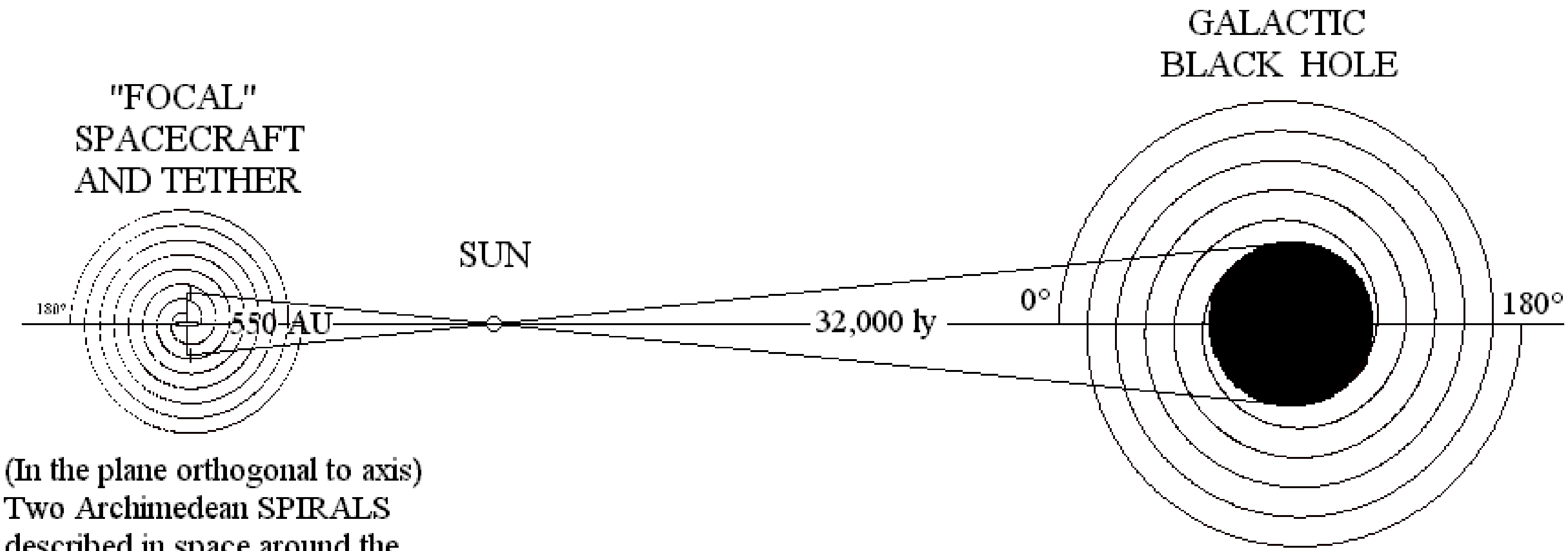


EXAMPLES: Three Targets

- We now provide THREE EXAMPLES of Targets for three different FOCAL missions:
- 1) The **Galactic Black Hole** (i.e. a FOCAL mission for Astrophysics and Cosmology).
- 2) The **Alpha Centauri** system of three stars, Alpha Cen A, B and C (Proxima) at 4.37 ly (basically a FOCAL mission to radio-explore the first target for any really interstellar mission).
- 3) Any **Extrasolar Planet**, for instance the Earth-size recently discovered Gliese 581 e.

#1 Target: Galactic Black Hole

"FOCAL" Spacecraft made up by TWO ANTENNAE TIED BY A TETHER ~ 2 km Long



(In the plane orthogonal to axis)
Two Archimedean SPIRALS described in space around the "FOCAL" spacecraft by each of two antennae tied to each other by a TETHER longer than 1.6 km.

(In the plane orthogonal to axis)
The corresponding two Archimedean SPIRALS described 32,000 light years away from the Sun, at the Galactic Center, around the gigantic Galactic Black Hole. Assuming its mass to be a million times the mass of the Sun, then its Schwarzschild radius equals 0,02 AU.

#1 Target: Galactic Black Hole

- From the similarity of the two triangles one gets:

$$\frac{Minimal\ Tether\ Length}{550\ AU} = \frac{2\ r_{Schwarzschild\ of\ Galactic\ Black\ Hole}}{32{,}000\ light\ years}$$

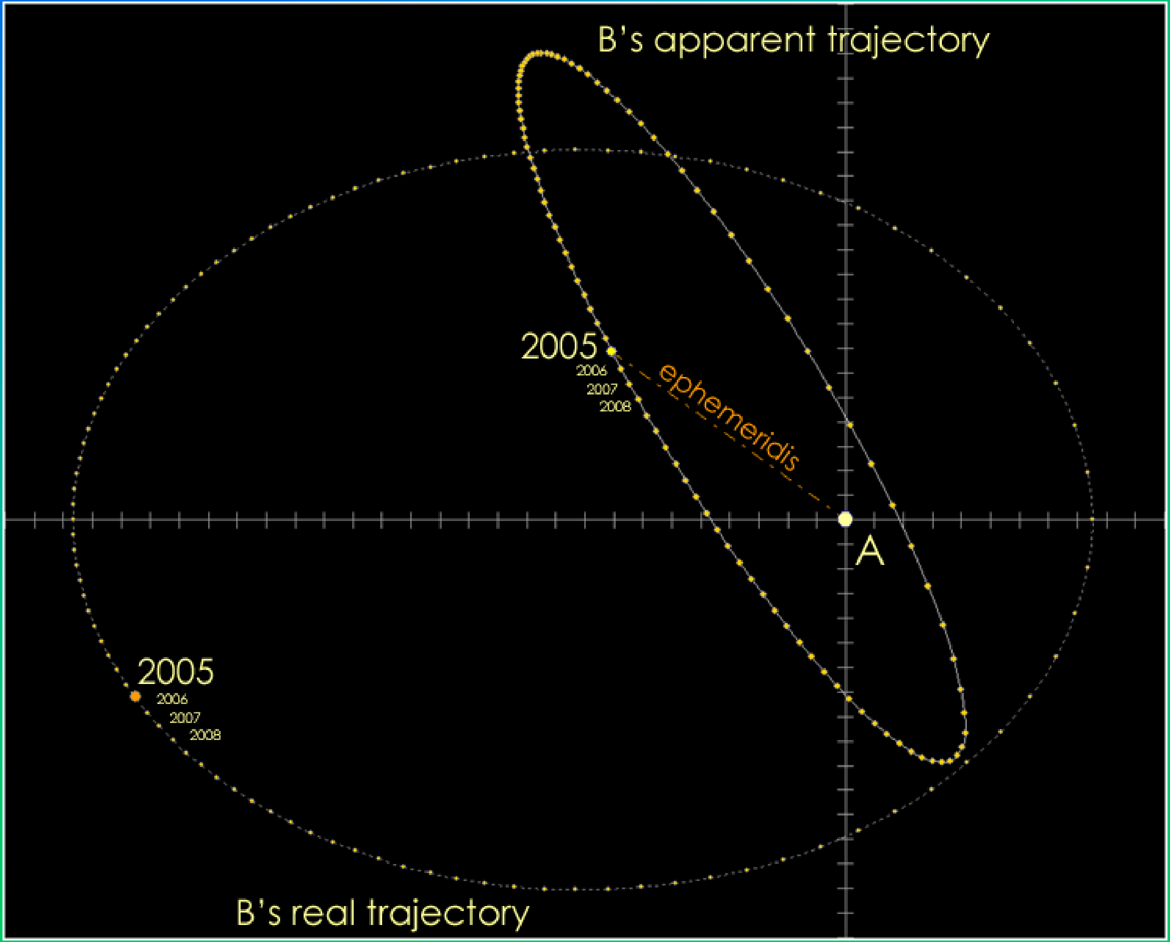
- Hence the ***MINIMUM TETHER LENGTH*** *:*

Minimum Tether Length *= 1.6 km.*

- ***IT CAN BE DONE !!!***

#2 Target: Alpha Cen A, B, C.

- Real and Apparent Orbits of Alpha Cen B wrt A:



#2 Target: Alpha Cen A, B, C.

- From the similarity of the two triangles one gets:

$$550 * AU * \tan\left(\frac{22 * \text{arcsec}}{2}\right) = 4.388 * 10^6 \text{km}$$

- Hence the ***MINIMUM TETHER LENGTH** :*

***Minimum Tether Length** ~ 1 Million km.*

- ***THIS TETHER CANNOT BE MADE !!!***

#2 Target: Alpha Cen A, B, C.

- But we can change the trajectory to a **CONICAL HELIX**, like the profile of the Guggenheim Museum in New York City:

#3 Target: An Extrasolar Planet

- For instance, consider **Gliese 581 e** (or **Gl 581 e),** the fourth extrasolar planet just found around Gliese 581.
- At a minimum of 1.9 Earth masses, it is the smallest extrasolar planet discovered around a normal star, and the closest in mass to Earth. See Wikipedia site.

#3 Target: An Extrasolar Planet

- The **LINEAR RESOLUTION** provided by FOCAL at distance z from the Sun and observing frequency ν is:

$$R_{Object} = d_{Sun\text{–}Object}\,\theta_{resolution} = d_{Sun\text{–}Object}\,\frac{c^2}{2\pi^2\sqrt{GM_{Sun}}}\frac{1}{\sqrt{z\nu}}.$$

- Here we know the object distance from the Hipparcos Star Catalogue, and we know the Focal distance z.
- ***Thus, we can select the observing frequency (one or many) at will: <u>THE HIGHER THE FREQUENCY, THE BETTER IMAGES</u> OF THIS EXOPLANET WE GET !!!***

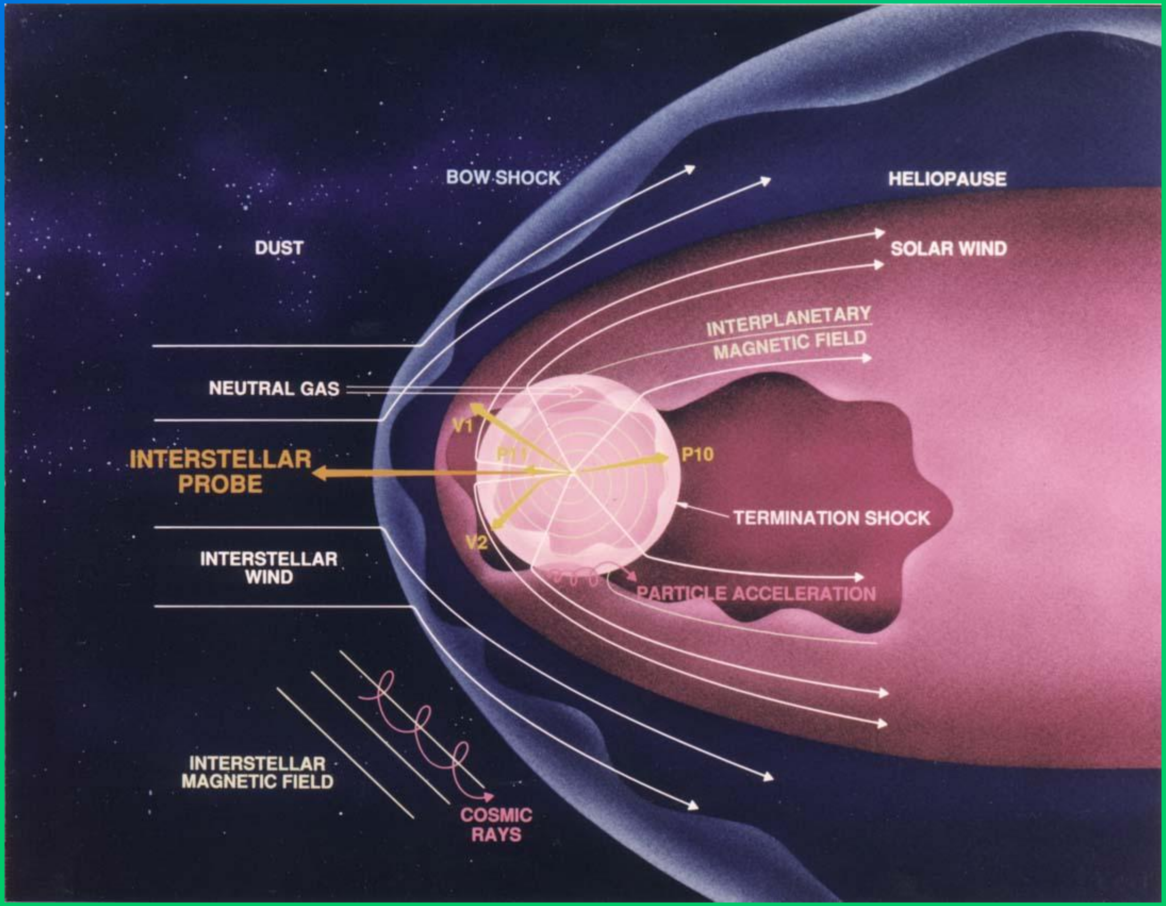
NASA Interstellar Probe (ISP)

Jet Propulsion Laboratory
California Institute of Technology

Interstellar Probe

Exploring the Interstellar Medium and the Boundaries of the Heliosphere

- **Interstellar Probe**
- **Exploring the Interstellar Medium and the Boundaries of the Heliosphere**



ESA Interstellar Probe

Proposal for an Interstellar Heliospheric Probe / Heliospheric Boundary Explorer Mission

in response to ESA's Call for Mission Proposals within the Cosmic Vision 2015-2015 Programme

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Thanks !