How Giovanni’s Balloon-Borne Telescope Contributed to Today’s Search for Life on Exoplanets

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Balloon-Borne Telescope

• 1970s: Bob Noyes suggests building an FTS for Giovanni Fazio’s 1-m telescope.

• Calculate Earth’s spectrum with Mark Stier.

• Get NASA grant to build FTS, with Nat Carleton.

• First flights from Palestine, Texas.

Earth spectrum calculation, Traub & Stier (1976)

Photos: John Brasunas, GSFC
Observing with 1-m Telescope

Measuring internal heat of outer planets with far-infrared photometer, with Stier, Fazio, Wright, Low (1978)

<table>
<thead>
<tr>
<th>Object</th>
<th>UT 1977 Apr 26</th>
<th>η (°)</th>
<th>δ (km)</th>
<th>φ (km)</th>
<th>S/N</th>
<th>P/P_thermal</th>
<th>T (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>10:32</td>
<td>40.23</td>
<td>7.1</td>
<td>28.7</td>
<td>43</td>
<td>&gt; 111 ± 10</td>
<td>0.1</td>
</tr>
<tr>
<td>Mars</td>
<td>10:35</td>
<td>4.58</td>
<td>10.1</td>
<td>28.7</td>
<td>18</td>
<td>720 ± 1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Saturn</td>
<td>04:03</td>
<td>17.46</td>
<td>1.4</td>
<td>28.7</td>
<td>22</td>
<td>2000 ± 2.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Uranus</td>
<td>04:47</td>
<td>4.07</td>
<td>1.6</td>
<td>28.9</td>
<td>40</td>
<td>0.027 ± 0.003</td>
<td>0.6</td>
</tr>
<tr>
<td>Neptune</td>
<td>02:28</td>
<td>2.31</td>
<td>1.3</td>
<td>28.7</td>
<td>2</td>
<td>0.0092 ± 0.0047</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Switching to spectroscopy of ozone layer in stratosphere (much easier!), with Chance, Johnson, Jucks (1981)

Measuring oxygen etc. on Venus & Mars etc. from the ground, with Noxon, Carleton, Connes (1976)

Getting interested in “beyond Hubble” telescopes with Carleton, Gursky, Lacasse, Shao (1985)
For many years, telescopes looked like this. We lived with diffraction & “seeing”.

Galileo, 1609

Herschel’s Reflecting Telescope, 1789

George Ellery Hale & Hooker Telescope, Mt. Wilson, ~1920
We learned the true sizes and compositions of the planets

Jupiter’s diameter is eleven times greater than the Earth’s, and it has over 300 times the mass.

*Fast-forward 20 years....*
Today’s telescope ideas are not as limited by diffraction and seeing, so we can ask the **Big Questions:**

- Are there Earth-like planets around nearby stars?
- Are there signs of life on these planets?

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**Space Interferometer Mission (SIM Lite)**  
*Proposed for coming decade*

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**Terrestrial Planet Finder Coronagraph/Occulter (TPF-C/O)**  
*Proposed for late in coming decade*

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**Terrestrial Planet Finder Interferometer (TPF-I)**  
*Proposed for next decade*
First claimed exoplanet image: 1RXS J160929.1-210524

Location: (16 h, -23 deg)
Upper Scorpius Association
Distance ~ 145 pc

Separation:
2.22 arcsec = 330 AU

Visible brightness ratio:
~ 1,000,000x or 15 mag

If this were a nearby star, the Earth’s orbit would be hidden in the glare.

Fomalhaut b
HR 8799 b, c, d
How do we find exoplanets?

- Radial velocity (the Doppler effect)
- Transits (a mini eclipse of the star)
- Gravitational lensing (Einstein said light bends near a star)
- Astrometry (elliptical motion on the sky)
- Infrared interferometer (several small telescopes working together)
- Visible coronagraph telescope (block the star inside the telescope)
- Visible occulter (block the star from far away)
If a star moves toward us and later away from us (owing to a planet), then its spectrum will be blue-shifted and later red-shifted.
Transit method

Spitzer: infrared

Corot & Kepler: visible

TrES-3b to Scale

31.3 hour orbit

Optical Axis

Schmidt Corrector 0.95 m dia.

Sunshade

Focal Plane Radiator

Graphite-cyanate Metering Structure

Local Detector Electronics

Focal Plane Array

42 CCDs, >100 sq. deg. FOV

Primary Mirror 1.4 m dia.

Relative Flux

0.97

1.01
Many of the new planets are too hot or too cold to support life.

This is the “Goldilocks” zone!
Terrestrial Planet Finder Coronagraph (TPF-C)
TPF-Coronagraph

Off-axis secondary mirror

V-shaped thermal shields

Coronagraph section

before

after

off-axis primary mirror
Lab demo of $(1 – \text{sinc}^2)^2$ mask

- Star image (no mask)
- Star image (with mask)
- Focal-plane mask
- Pupil-plane stop
- Deformable mirror

500 D-shaped images of dark hole,
Rotated to sample annulus on sky,
Planets added,
Common speckles removed,
Planets pop out of noise.

Shows that Earth could have been detected.

Shaped-pupil mask

Spergel-Kasdin prolate-spheroidal mask  dark areas \(< 10^{-10}\) transmission  PSF cut along horizontal axis

Kasdin, Vanderbei, Littman, & Spergel, 2004
\[ E_{\text{out}}(\tilde{x}, \tilde{y}) = A_{\text{out}}(\tilde{r}) \iint \frac{1}{\lambda Q(\tilde{x}, \tilde{y}, x, y)} e^{2\pi i Q(x, y, y) / \lambda} A_{\text{in}}(r) \, dy \, dx \]

Input wavefront from star has uniform amplitude.

Pupil Mapping:
Image of star is \( \sim \)gaussian with very weak “Airy rings”.

Terrestrial Planet Finder Interferometer (TPF-I)
TPF-Interferometer

1. star, planet, & zodiac, seen as a single (not resolved) blob by each telescope

2. four collector telescopes & one combiner, plus delay lines, all free-flying

3. transmission pattern, times sky image, seen as a single blob; total amount of light received is noted

4. array rotates

5. measured total light level, as array rotates a full turn (bumps are the planet)
Terrestrial Planet Finder Occulter (TPF-O)
• Big telescope (planet is faint!)
• Big occultor (few times size of telescope)
• Big separation (to see close to star)
Spectra
Visible Earthshine Spectrum

- Rayleigh
- Ozone O$_3$
- Chlorophyll 720 nm edge
- Water H$_2$O
- Oxygen O$_2$

Marked features show habitability & signs of life

- Observed Earthshine, reflected from dark side of moon.

Habitability of an Earth-like Planet

- **measured**
  - TPF-C: Molecular column
  - SIM: Mass
  - TPF-I: IR flux
  - TPF-I: IR color
  - TPF-C: Vis flux
  - TPF-C & TPF-I: Vis & IR spectra

- **derived**
  - Radii
  - Albedos
  - Greenhouse warming
  - Lapse rate of atmosphere
  - Scale height of atmosphere
  - Surface & cloud reflectances

- **implied**
  - Surface pressure
  - Density of planet
  - Surface gravity
  - Eff temp.
  - Type of planet
  - Presence of H₂O
  - Cumulus, cirrus, ice, rock, sand, water
  - Likelihood of plate tectonics & atmosphere retention

- **Type of planet**
  - TPF-C
  - TPF-I
  - SIM

- **Likelihood of plate tectonics & atmosphere retention**
  - TPF-C
  - TPF-I
  - SIM
Planets vs zodi: telescope size matters

Ref.: (upper) M. Postman et al., ATLAST study; (lower) W. Cash et al., NWO study.
Species SNRs & abundance uncertainties


Bottom line: An 8-m telescope can characterize nearby Earths, and search for signs of life.

Thank you!

And thanks, Giovanni!!
A Tale of Two Geometries

Transit

Direct Imaging

Traub 28
Visible Radius