STATUS OF SPACE BASED CORONOGRAPHIC MISSIONS

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introduction

coronographs in space: HST/NICMOS-STIS

Flying soon: JWST/MIRI-NIRCAM

old proposals: TPF-C, SPICES

WFIRST-AFTA

Other proposed missions: Exo C, Exo S, Excede, Maple
- occulting hole in the Camera 2 FDA mirror
- internal cryogenic mask located at the Lyot plane.
- glints limit to > 0.4 arcsec
- contrast : $\sim 10^{-4}$ @ 0.4 arcsec
- image example:

HR4796A circumstellar disk (Schneider et al, 1999)
1 occulting bar + 2 wedges

- limited apodization via a Lyot stop
- status: still in operation
- Schneider et al. 2014

HD 107146 (G2V) $f_{\text{disk}} / f_{\text{star}} = 0.0077\%$

http://www.stsci.edu/hst/stis/
MIRIM: imager, under French leadership, with coronographic capability

Goals:
- Jovian planets around close stars
- Circumstellar disks, AGN

3 4QPM: 10.65/11.4/15.5μm, 1 Lyot at 23 μm

Lyot stops on filter wheel

Fine pointing using FSM: few mas 1 sigma

Status:
- AIT phase at NASA Goddard
- February 20, 2014: mounted on instrument payload module (ISIM)
- Launch end 2018
corono : lab. performance, (bocaletti 2014)
corono + telescope : simulations, depends on
  - Pointed target
  - Assumption on WFE error
  - Assumption on noises
  - Reference star subtraction process

~$10^{-5}$ contrast @ 4-6 $\lambda/D$ seems achievable (10 $\mu$m)

F1140C, No noise, WFE 130 nm, PSF plain, with corono dotted, with ref image sub. dash dotted – blue WFE more pessimistic

Include pointing errors, more pessimistic WFE

Lajoie et al 2014 (SPIE)
- Nircam has also a coronographic mode
- five occulters on a transparent plate
- 3 radially-symmetric occulters with “sombrero” profiles
- 2 wedge-shaped occulters with sinc2 profiles
- Apodized masks in the lyot plane on a wheel
TPF-C (1/2)

- studies in the US 2000-2008
- main document (JPL)
  - TPF-C flight Baseline Mission Concept (2009)
- goals:
  - Main: discover and study exo-earths in the HZ around nearby stars
  - others: giant planets, disks, general astrophysics
- spectral range: 0.5-1.1 µm, spectral resolution: \(\lambda/\Delta\lambda = 70\)
- deployable M2 and sun shade
- L2 orbit, launcher Delta IVH, launch mass 8 tons
- cost = JWST class...
- status: cancelled in 2008
FB1 optical design

- FOV = +/- 5 arcsec
- order 8 Lyot coronograph @ $4 \lambda/D$
- $10^{-10}$ contrast
- IWA = 65 mas, OWA = 500 mas
- M1: 8 x 3.5 m elliptical, off-axis – f1=13.4 m
- EFL = 140 m, tel height=12 m
- Off axis Ritchey-Chretien
- straylight level $6 \times 10^{-11}$ of stellar peak brightness
- 4 IFS - $\Delta \lambda/\lambda=20\%$
- 1 Wide field camera
SPICES (1/2)

- proposed for M3 CV Call in 2010 – (Seacoast => SPICES)
- european consortium led by A. Boccaletti
- main document : CV M3 proposal
- spectro-polarimetry in the visible, with main goals :
  - Long period giants (0.5-10 AU), < 20pc
  - Close super earths (0.5-2 AU), < 5pc
  - Atmosphere properties, formation process, exozodi,…
- 400-800 nm, 2 bands
- spectral resolution : $\lambda/\Delta\lambda=50-100$
- L2 orbit, Soyuz, launch mass ~2 t
- cost = > ~ 600 ME => not a M mission
- Current status : not submitted to M4 call

Table 10: Summary of pointing requirements for SPICES

<table>
<thead>
<tr>
<th>Stage</th>
<th>Spacecraft</th>
<th>Telescope</th>
<th>Coronagraph</th>
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<tr>
<td>1st stage</td>
<td>&gt;10&quot;</td>
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<tr>
<td>2nd stage</td>
<td>10 - 100mas</td>
<td>1-10 mas</td>
<td>0.1 mas</td>
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<td>3rd stage</td>
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SPICES (2/2)

- optical design
  - 3 mirrors afocal telescope (2 OAP: + 1 pure elliptical concave mirror)
  - 64 mm pupil on DM
  - M1 : 1.5 m
  - FOV = +/- 6 to 12 arcsec
  - $10^{-9}$ to $10^{-10}$ contrast
  - Charge 4 Vortex corono. $1.8 \frac{\lambda}{D} - 2.4 \frac{\lambda}{D}$
  - IWA = > 100 mas
  - WFE static : 20 nm rms, fine control : 10 pm rms (SCC/EFC + 64 x 64 boston DM)
  - 2 IFS
WFIRST-AFTA
Wide Field Infrared Survey Telescope

- WFIRST: NIR mission recommended in 2010 US decadal survey, answer to *New Worlds, New Horizons* (NWHN)
- AFTA = Air Force Telescope Assembly, Ritchey-Chretien, D=2.4m 250M$

- Goals:
  - Determine the nature of the dark energy
  - Statistical census of planetary systems through microlensing survey
  - Survey the NIR sky / provide the community with a wide field telescope for pointed wide observations
  - Giant planets and debris disks with coronograph
WFIRST-AFTA DESCRIPTION

- launch 2020-2025
- Cost class : 1-1,5 Billion $
- geosynchronous orbit (L2 ?)
- mass
  - Satellite : ~7,5 t
  - Telescope : ~ 1,8 t
  - Instrument : ~ 700 kg

Wide-Field Instrument
- Imaging & spectroscopy over 1000s of sq. deg.
- Monitoring of SN and microlensing fields
- 0.7 – 2.0 micron bandpass
- 0.28 deg² FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 6 filter imaging, grism + IFU spectroscopy

Coronagraph
- Imaging of ice & gas giant exoplanets
- Imaging of debris disks
- 400 – 1000 nm bandpass
- $\leq 10^{-9}$ contrast (after post-processing)
- 100 milliarcsec inner working angle at 400 nm
Status (from a NASA talk, nov. 2014):

- Currently in “pre-formulation phase” - (pre-phaseA)
- AFTA endorsed by NRC study report released March 2014.
- Interim SDT report posted April 30, 2014
- SDT final report due Jan 2015
- FY14 appropriation ($56M) supports preformulation of WFIRST/AFTA, including:
  - technology development for detectors and
  - coronograph (with STMD)
- coronograph instrument still to be confirmed in 2015
WFIRST-AFTA: NRC REVIEW ON CORONOGRAPGH

- US National Research Council review Performed in January-February 2014 to determine if WFIRST-AFTA meets the WFIRST requirement in NWNH

Finding 2-6: Introducing a technology development program onto a flagship mission creates significant mission risks resulting from the schedule uncertainties inherent in advancing low technical readiness level (TRL) hardware to flight readiness.

Finding 1-7: The WFIRST/AFTA coronagraph satisfies some aspects of the broader exoplanet technology program recommended by NWNH by developing and demonstrating advanced coronagraph starlight suppression techniques in space.

Recommendation 2-1: NASA should move aggressively to mature the coronagraph design and develop a credible cost, schedule, performance, and observing program so that its impact on the WFIRST mission can be determined. Upon completion ... an independent review.
french and UK scientist expressed interest to participate to a coronograph instrument in WFIRST-AFTA

experience of LAM, LESIA, OCA LAGRANGE in coronography, ground or space based (MIRI, SPHERE, THD SCC, SPEED,...)

CNES R and D contributes to a high expertise level and detailed experimental work in the field

CNES supports and encourages participation in WFIRST-AFTA based on a TBD contribution in the appropriate labs

Cornograph seems excluded, as well as fine WFE measurement/control

Another subpart of the instrument has to be identified: Optics ? Detectors ? Electronics ? Tests ?

a consortium should be build to organize this and study the various possibilities

planning is important for CNES => When will the funding will be necessary ?
CNES R and D EFFORT

- CNES R and D in HRA and coronography
  - 2000-2003: LESIA, support to first 4QPM→ MIRI
  - 2003-2010: IR interferometry (Synapse, Persée,…), european priority
  - 2010-2014: LESIA, Self Cohernet Camera, 1 PhD
  - 2014: + ONERA phase diversity for coronography, 1 PhD
  - 2015:
    - PIAA for SPEED at OCA and Vortex at LESIA
    - prospective action with LAM, possibility of making a boston-like DM in Europe (german design, switzerland fab., test at LAM – 32 x 32 actuators)

- simple breadboard at CNES started in 2014, monochromatic, $10^{-7}$ contrast
  - DM techno/WFE sensing complementary to OTOS (earth observation)
  - Goal: better understand the basics to better address key questions for space application in the future: space qualification, pointing, thermal stability
EXO-C (~US version of SPICES) – interim report April 2014

- 1.5 m, unobscured Cassegrain, 450-1000 nm
- 1 x 1 arcmin FOV
- Earth trailing orbit
- $10^{-9}$ raw contrast, ~2 -20 $\lambda$/D,
- PIAA/Vorte/hybrid Lyot +DM
- Pointing stability 0.1 mas at instrument level
- Launch mass ~1.8t
- Launch date: 2024 (2017 start)
- 750 M$ estimated cost (Kepler heritage)
- Status: final report jan. 15, evaluation by NASA in 2015 (probe class mission)
EXO-S – NASA interim report April 2014

- Jupiter down to earth around close stars
- Occultor at long distance in front of telescope
- Classical visible telescope (Nextview, 1.1 m)
- $10^{-10}$ contrast IWA 75 to 115 mas, FOV 1 arcmin
- Mass: 1.2 + 1.4 t
- D: control +/- 250 km
- Relative DX/DY: control +/- 1 m, sensing 20 cm (1 mas)

Straylight?

Figure 6.1-1. Image plane contrast at 700 nm with no lateral error (left), 1 m error (center), and 1.2 m error (right).
Smaller missions: excede

- Excede (G. Schneider presentations)
  - Nasa Ames / University of Arizona – G. Schneider / O. Guyon
  - Circumstellar disks + technological
  - Raw contrast goal $10^{-6}$ to $10^{-7}$ @ $1.2 - 2 \lambda/D$
  - IWA 0.14" @ 0.4 µm, PIAA coronograph
  - 0.7 m off axis telescope
  - Status: 2013 => approved for two-year Tech. Dev program
Smaller missions: maple

Maple – (Christian Marois – SPIE paper)

- National Research Council of Canada, University of Victoria
- Stratospheric balloon
- Few Jovians/ice-giant around nearest stars. + techno.
- Contrast goal few $10^{-8}$ @ $1.7 \lambda/D$
- Vortex coronograph + SCC
- 0.5 m off axis telescope, 3 spherical mirrors (M1, M2, M3)
- CNES Carmes gondola
- Pointing requirement: 5 mas RMS, very challenging under a balloon
- Status: ?
WFIRS Nov. 2014, Exoplanet splinter session, summary

Angular Separation (arcsec)

Planet/Star Contrast

Self-luminous planets
Known RV planets
Solar System planets

GPI
HST
JWST

Maple

TMT / ELT

TPF-C ~EXO-C/SPICES

Venus
Earth
Mars
Saturn
Uranus
Cost of a dedicated mission is very high (> M size mission), even for a reduced size telescope due to:

- very demanding performances: pointing, telescope stability, WFE fine control, straylight, ...
- Low TRL of new key components and technology: DM, coronographs, WFE measurement

small FOV of a dedicated mission make it difficult to include more general purpose astrophysics

- transit analysis is currently preferred because more mature
- ESA: no directing imaging mission before... L4 (means launch 2040) if recent long term programmation remains unchanged (L2 Athena, L3 Lisa)

- try to couple coronography with other mission, although the telescope is no more optimized
  - Astrometry+corono (as proposed by O. guyon)
  - Dark energy + corono = WFIRST-AFTA + Corono

- if no coronograph on WFIRST, then Exo-C/Exo-S?
- Or go to smaller mission for techno demonstration (Excede, Mapple?)
PERFORMANCES COMPARISON

Lawson 2013 + WFIRST-AFTA added