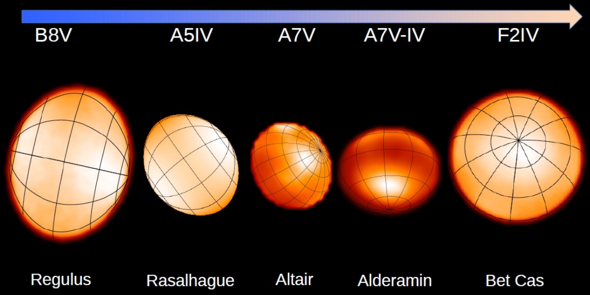
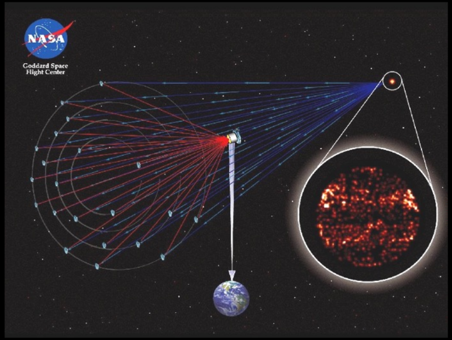
Imaging the Surfaces of Distant Stars with Sub-Milli-Arcsec Resolution: Extending Ground-Based Interferometry into Space

Updated 2024, 29 Feb





Dr. Kenneth Carpenter

@KenAstro (Twitter) & @KenAstro1804 (IG)

NIAC Fellow 2024

HST Operations Project Scientist

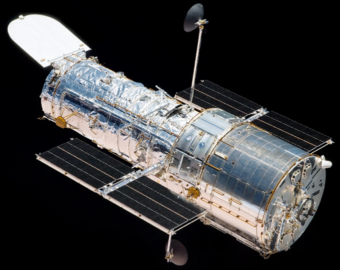
RST Ground System Scientist

NASA Goddard Space Flight Center

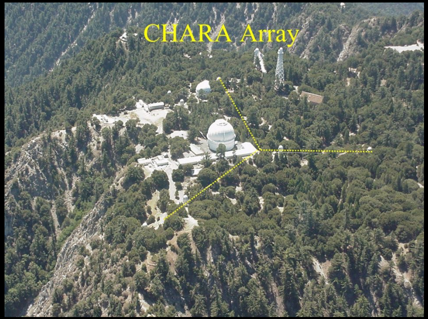
Outline

Progress so far:

Single Mirror Space Telescope

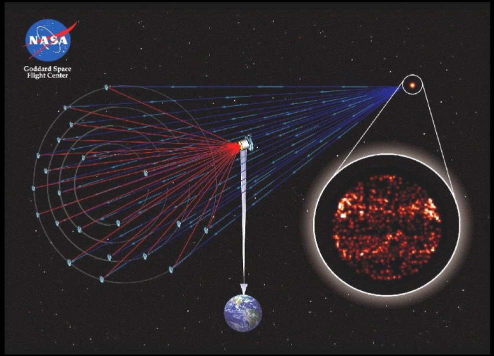


Ground-Based Interferometers

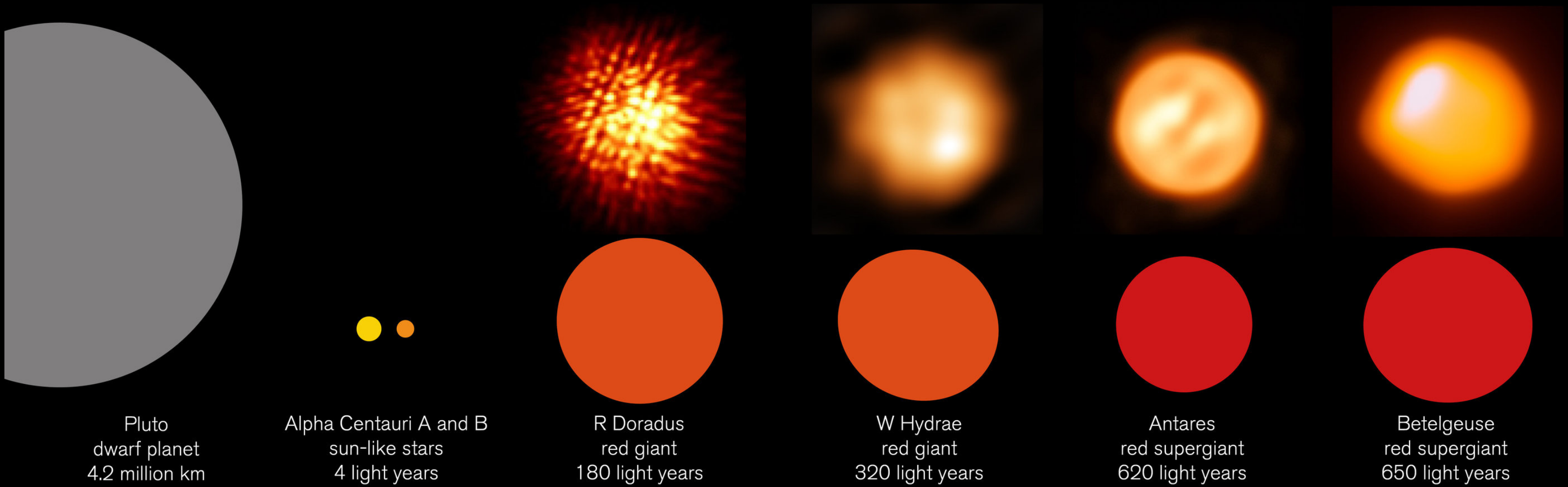


Space Interferometers

The Future:



Only the biggest and closest stars can be imaged directly



First Direct Images of Stars with Single Mirror telescope

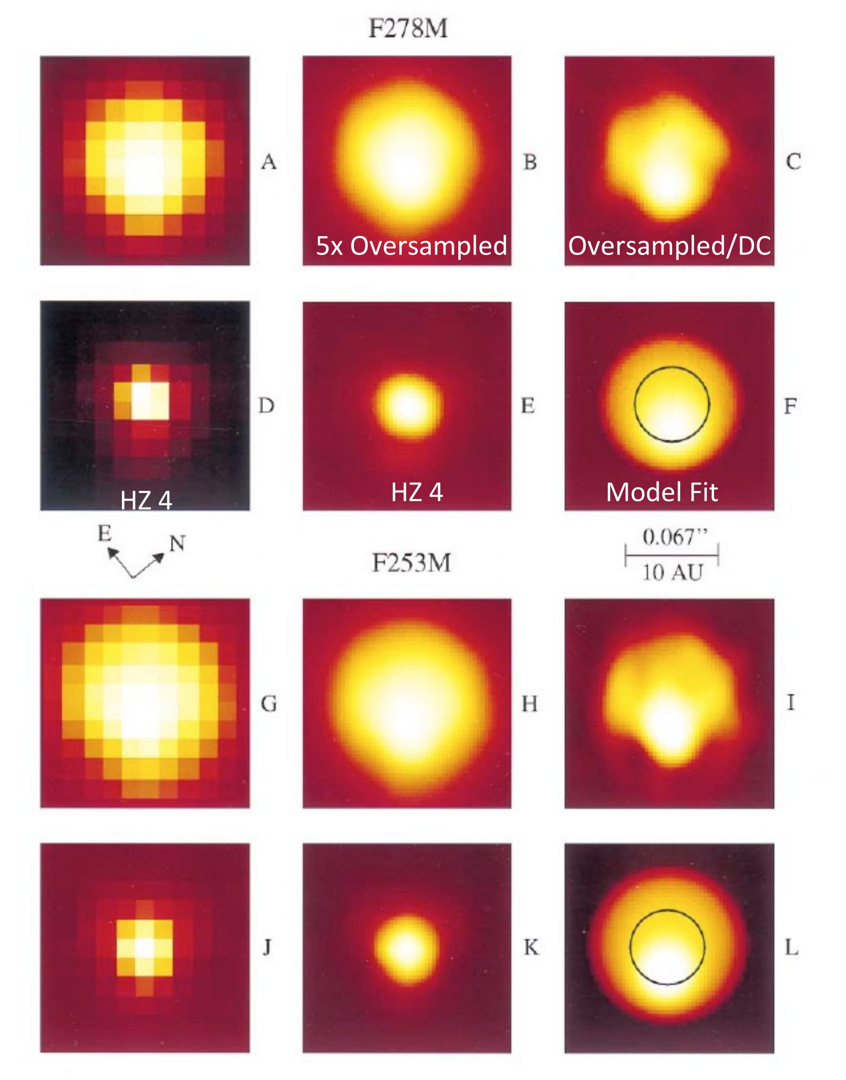
- **Hubble Space Telescope (HST):**
  - using the Faint Object Camera (FOC) in ultraviolet & visible light
- **Stars:**
  - Betelgeuse (Alpha Ori)
  - Mira ("the Wonderful")

First image of Surface of a Star with HST:

Faint Object Camera

Near-Ultraviolet image of Alpha Ori

Gilliland and Dupree 1996, ApJ, L29

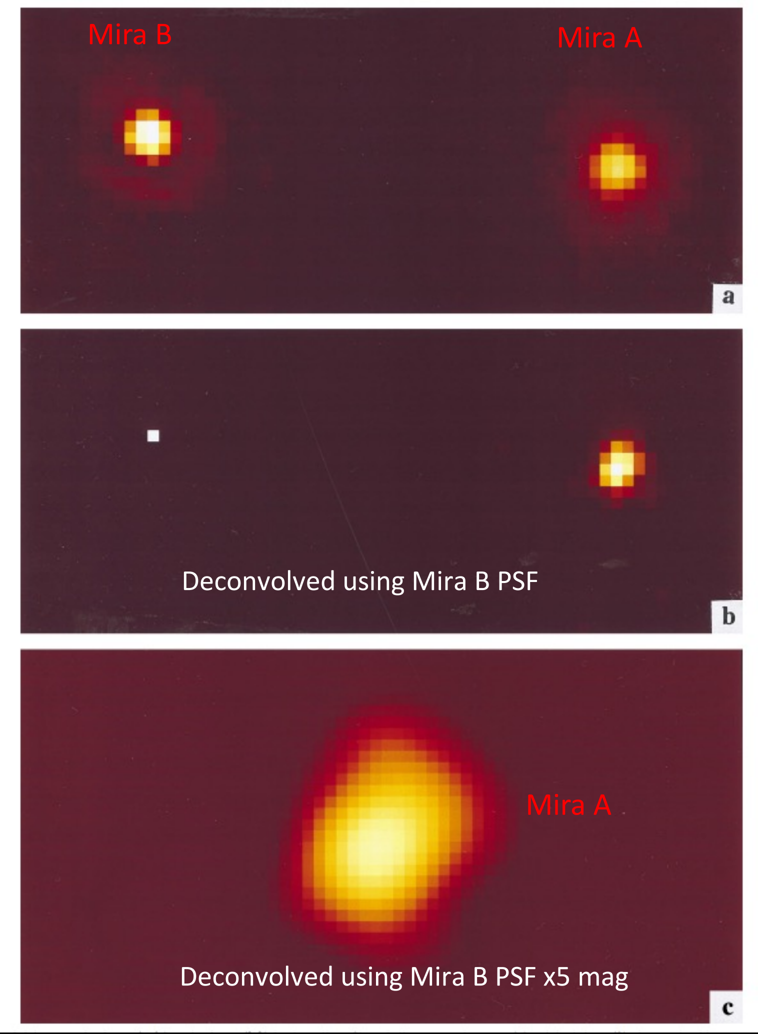


Second Star imaged with HST:

Faint Object Camera images from far-ultraviolet to mid-optical of Mira system

For the first time:
(1) Binary resolved
(2) Asymmetry in Mira A

Karovska et al. 1997, ApJ 482, L175



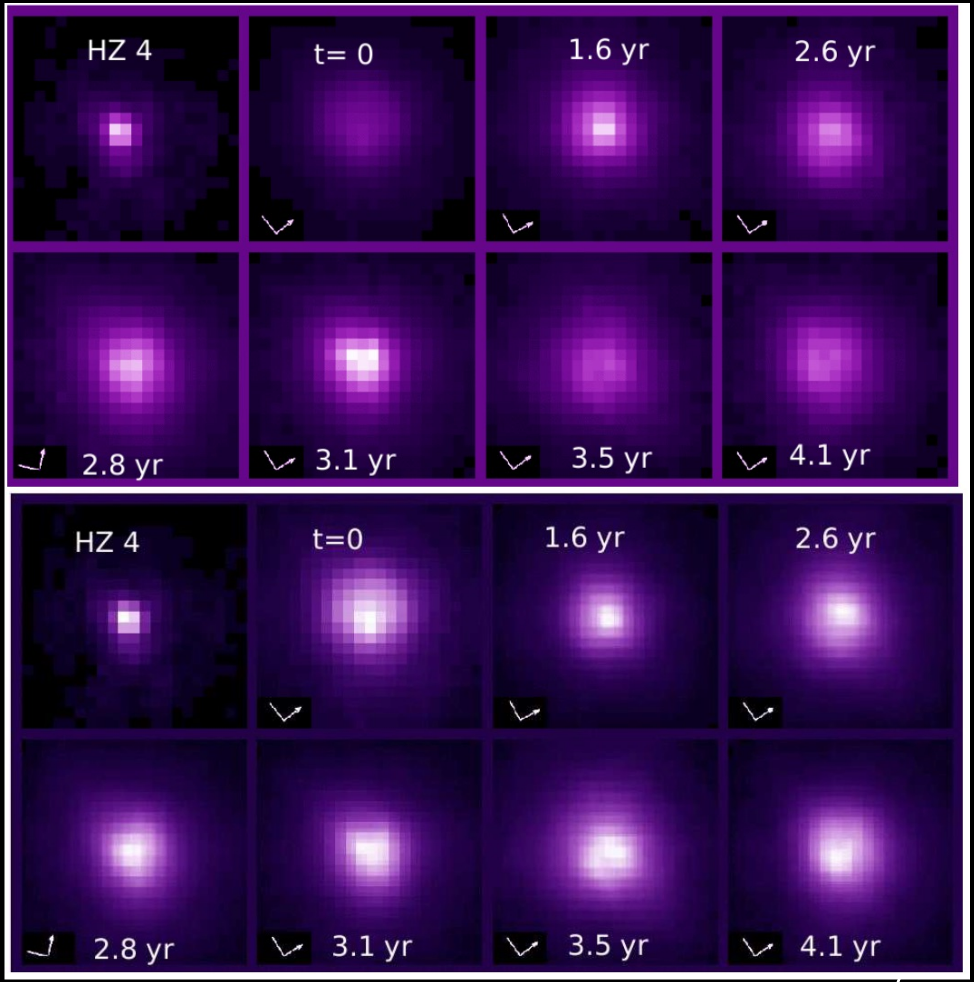
Time series of α Ori (Betelgeuse)

FOC near-ultraviolet images

Top: scaled to the same exposure ~3600s → actual light variation (~months)

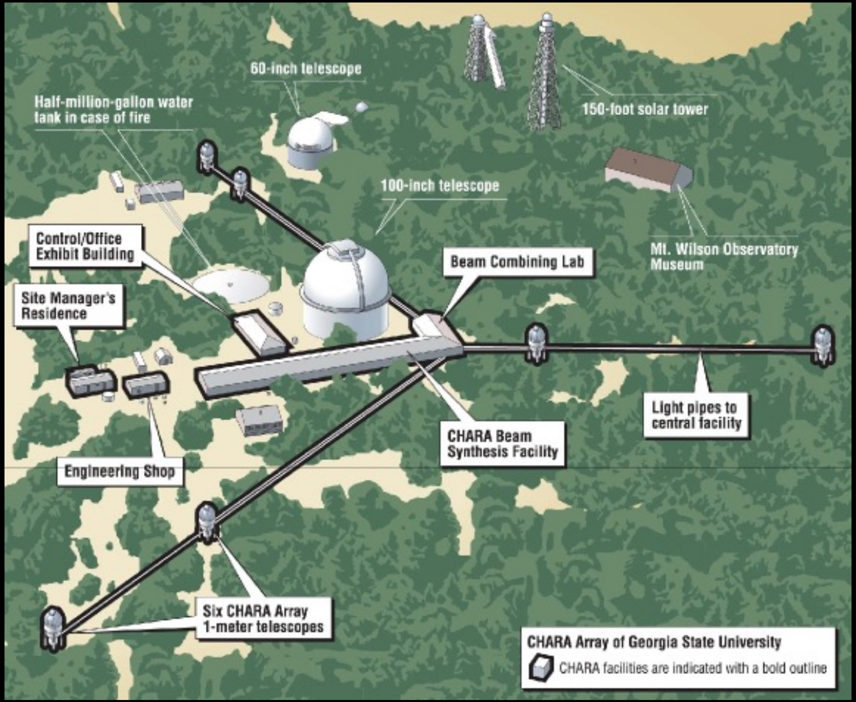
Bottom: scaled to the brightest pixel, to see as much detail as possible → changing brightness pattern.

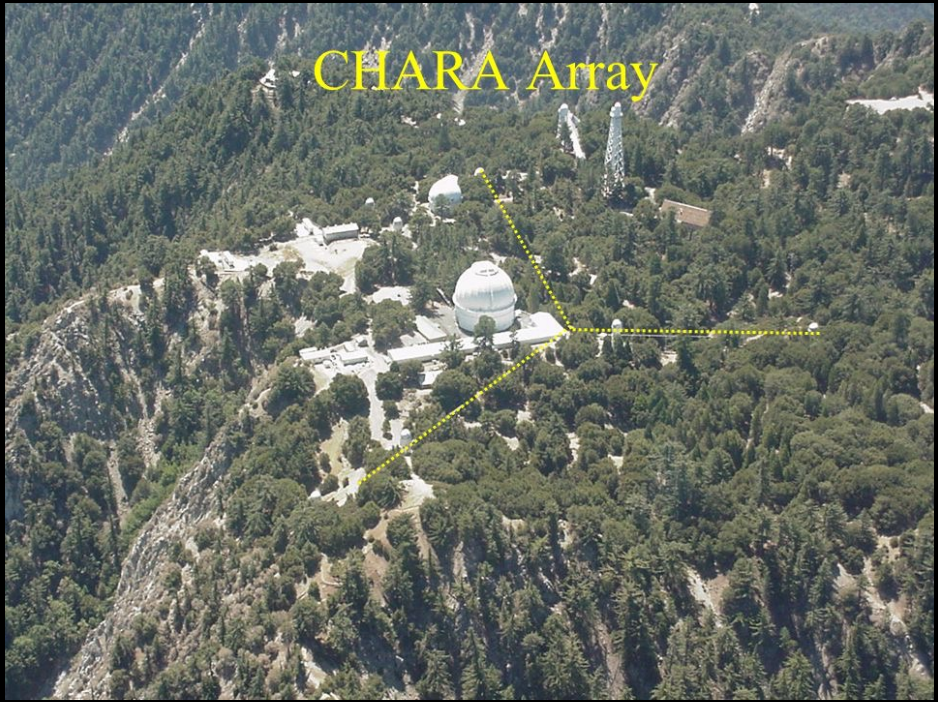
Dupree & Stefanik (2013)



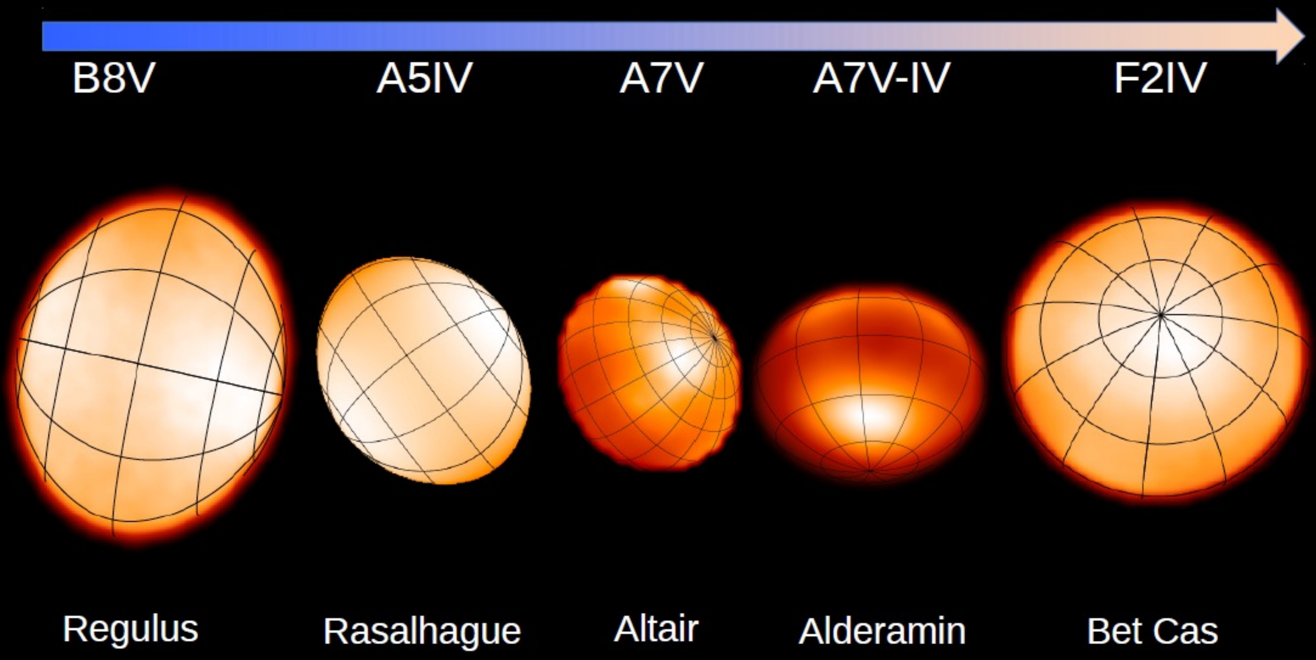
Imaging with Ground-Based Interferometers

CHARA (Center for High Angular Resolution Astronomy) Interferometer

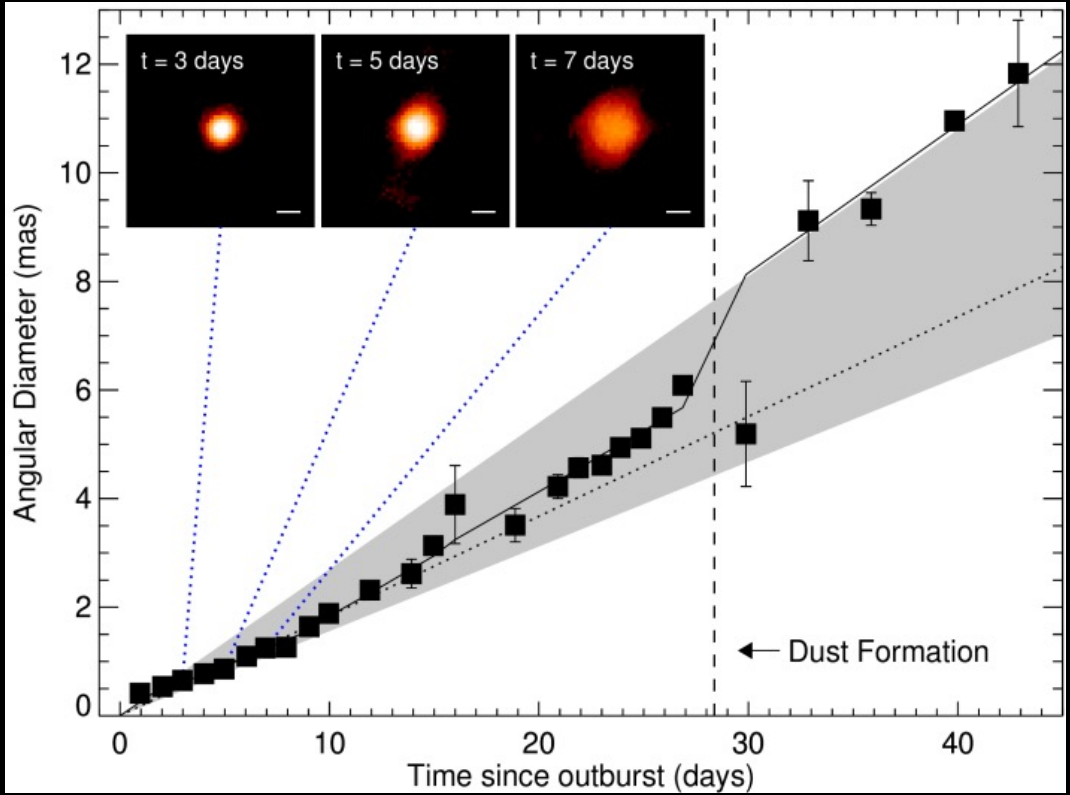




The Rapid Rotator Hall of Fame

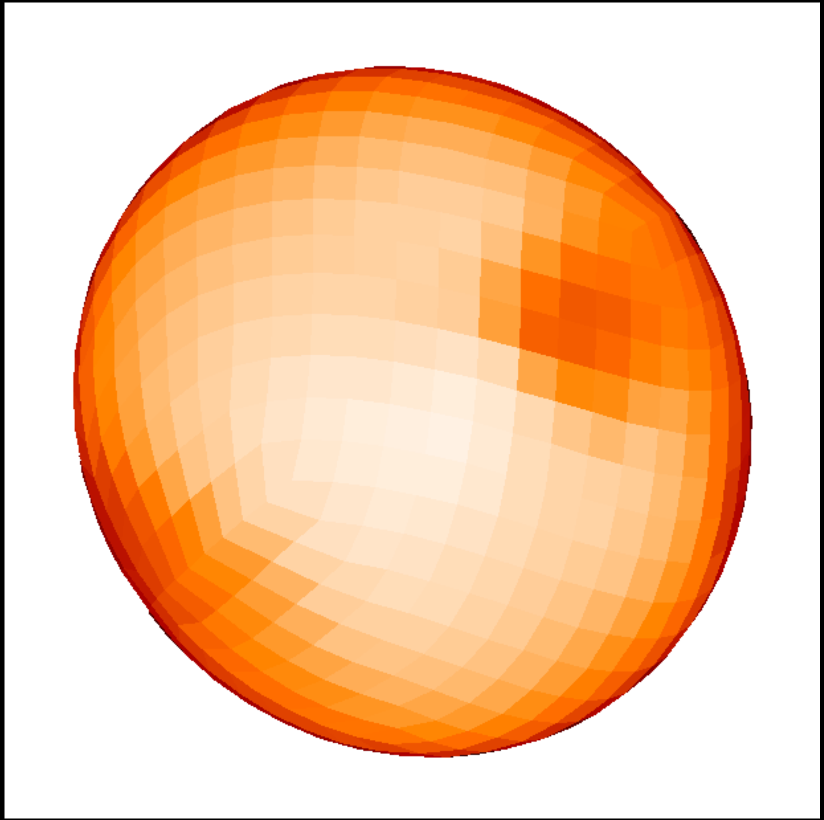


Nova Del 2013



Schaefer et al. 2014,
Nature, 515, 243

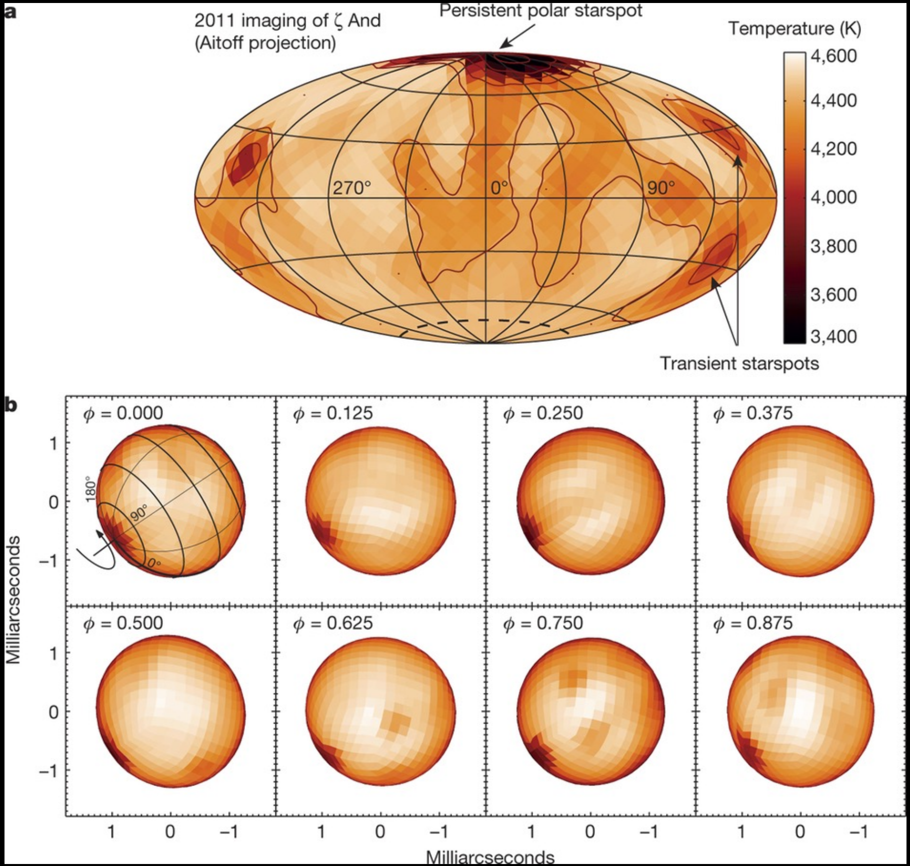
ζ And (2011)



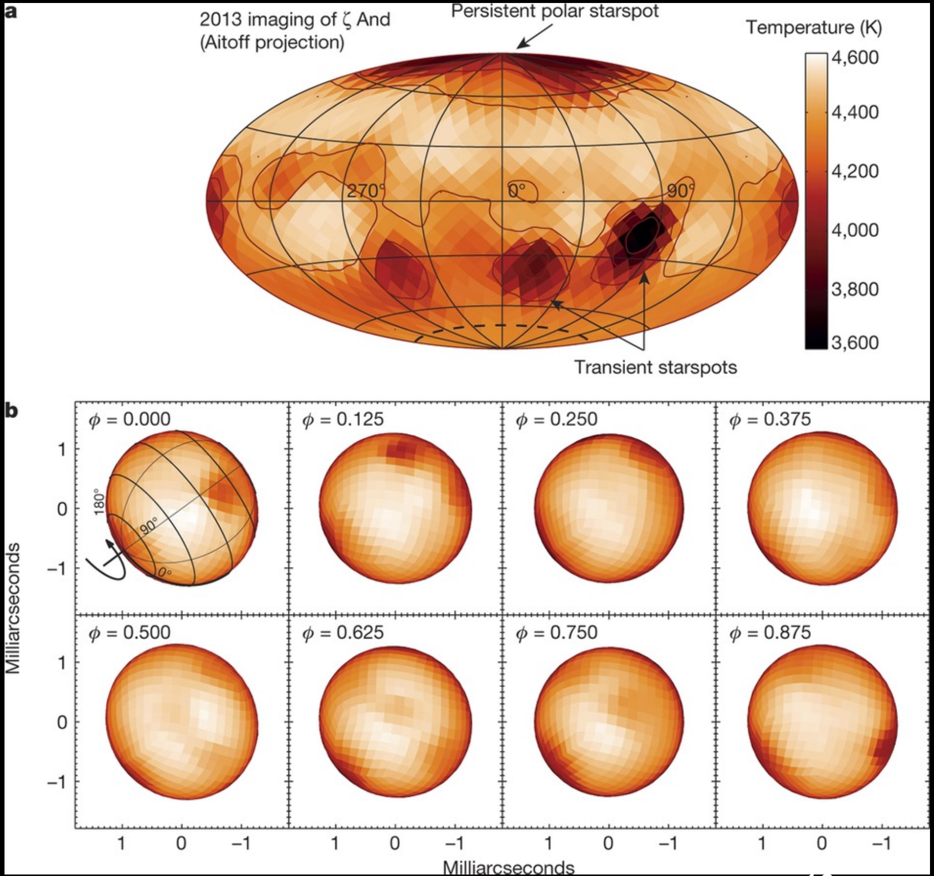
Roettenbacher et al. 2016, Nature, 533, 217

ζ And

2011



2013

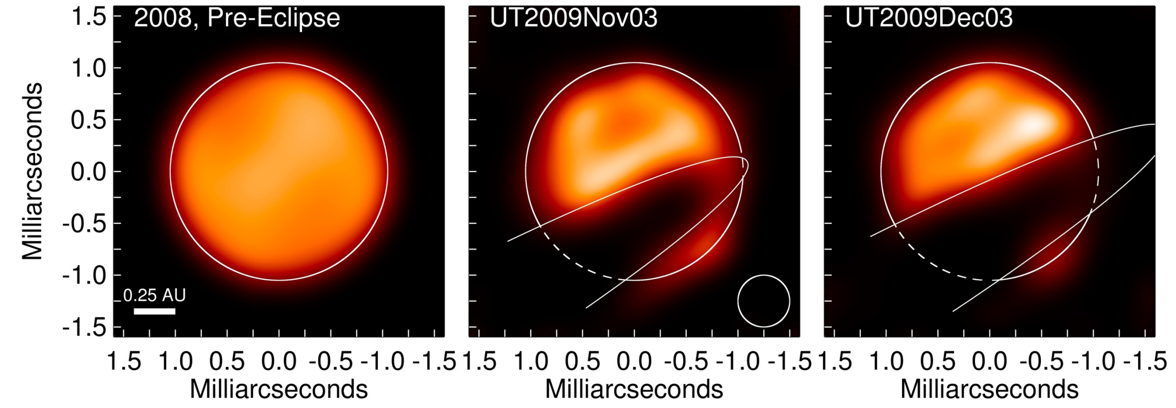


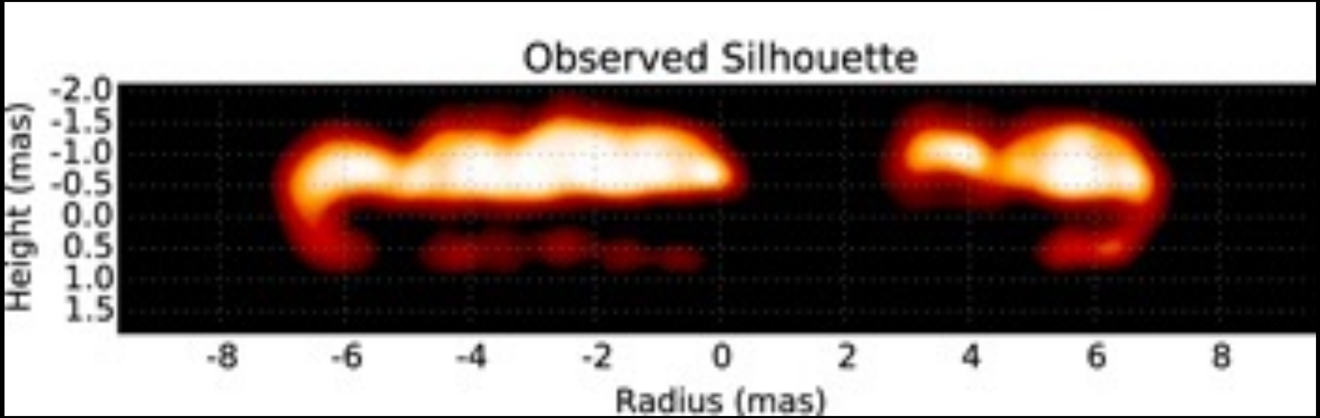
Roettenbacher et al. 2016, Nature, 533, 217

Beta Lyrae

Zhao et al. 2008, ApJ, 684, 95

Epsilon Aurigae



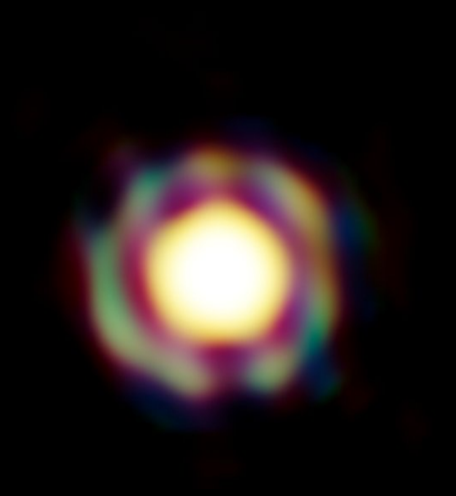


Kloppenborg et al. 2010, Nature, 464, 870; Kloppenborg et al. 2015, ApJS, 220, 14

The Very Large Telescope Interferometer (VLTI) – Cerro Paranal

Credit: G. Hudepohl/ESO

The Mira-like star T Leporis as seen with VLTI (2/2009)

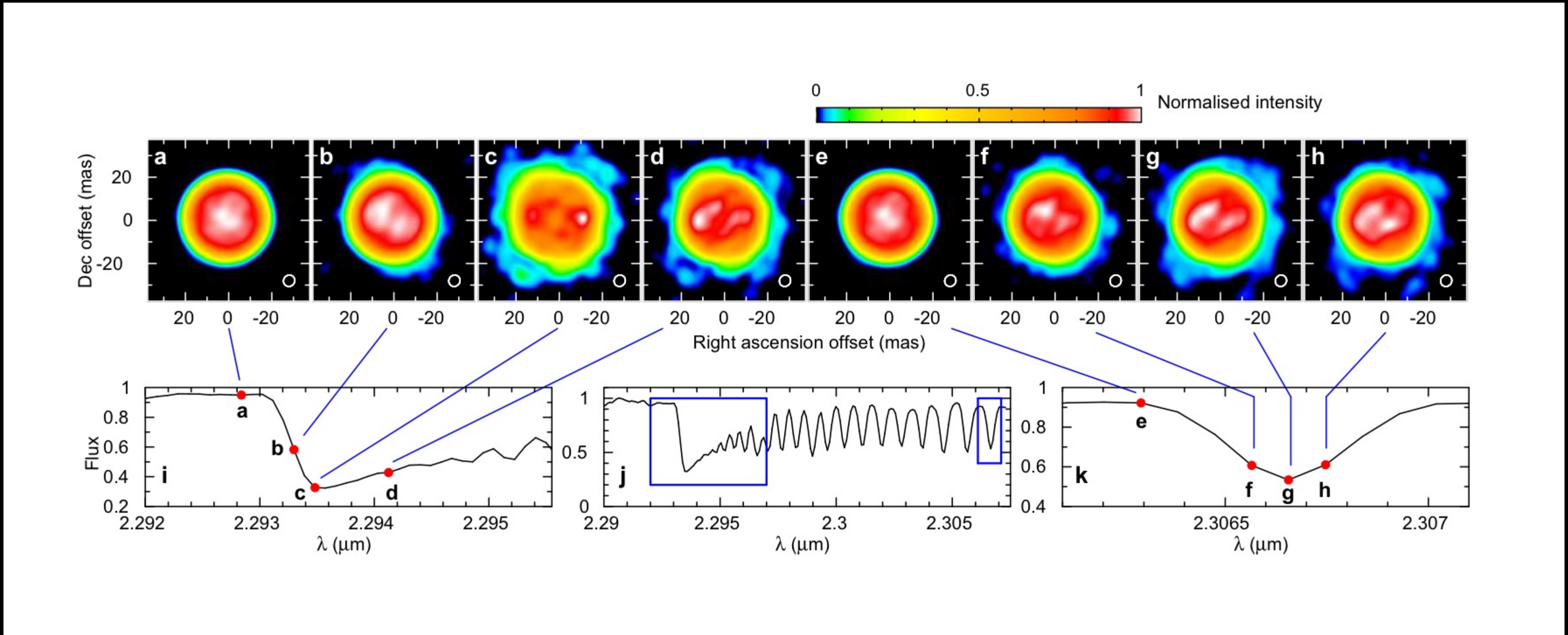


Credit: ESO/J.-B. Le Bouquin et al.

The surface of the star is surrounded by a spherical shell of molecular material expelled from the star.

Antares (VLTI, 2017)

Antares (2017)

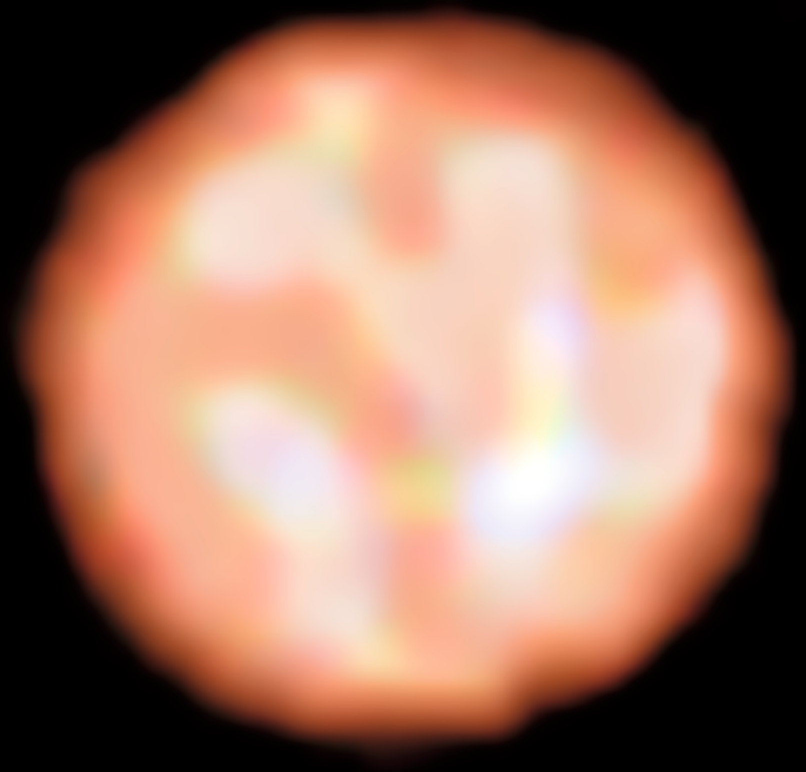


Reconstructed velocity-resolved images of Antares in the molecular bands, observed with VLTI/Amber

K. Ohnaka, G. Weigelt & K.-H Hofmann

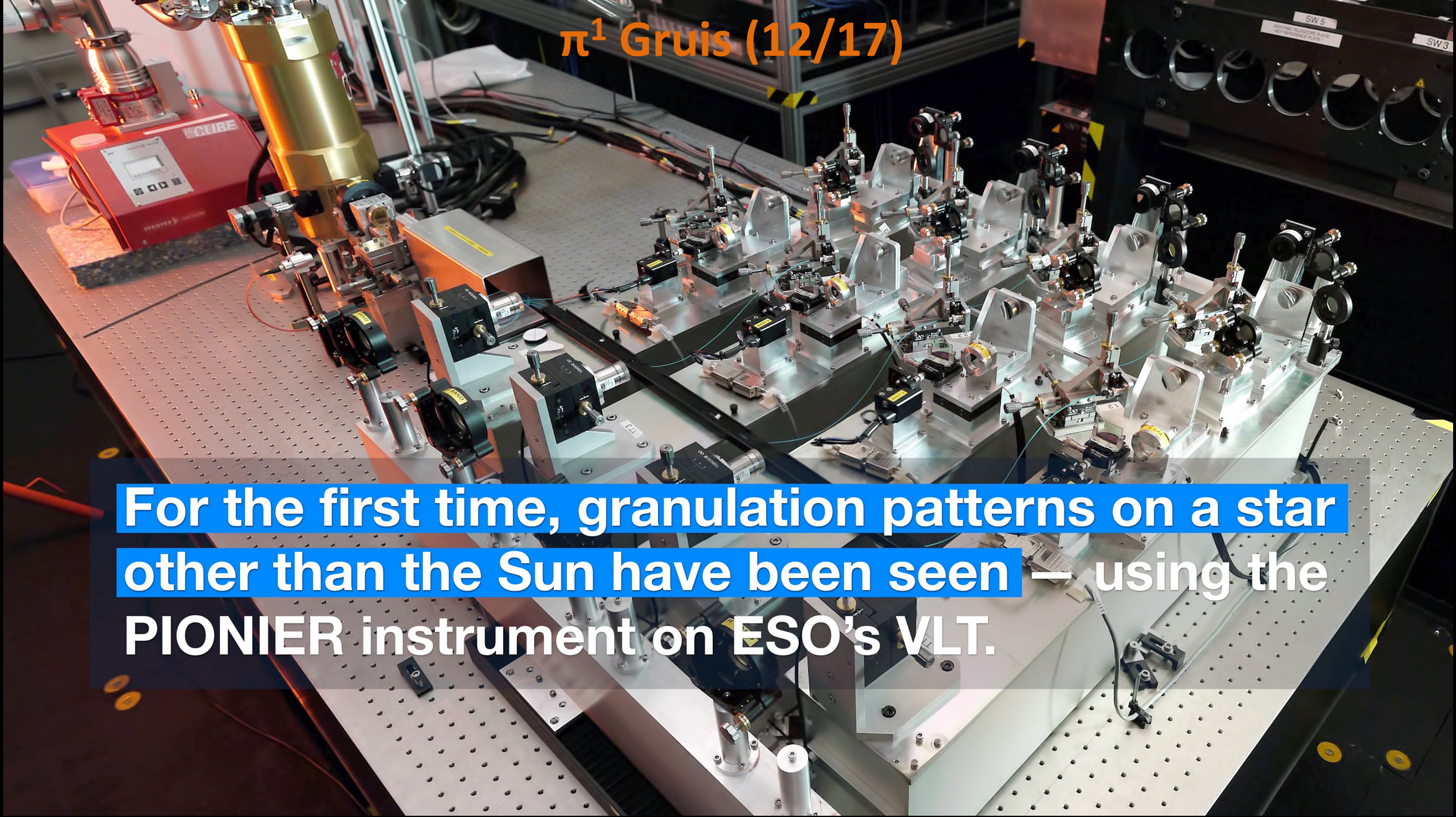
π^1 Gruis (12/17)

Granulation patterns on the surface of the red giant π^1 Gruis with the PIONIER instrument.



Credit: ESO

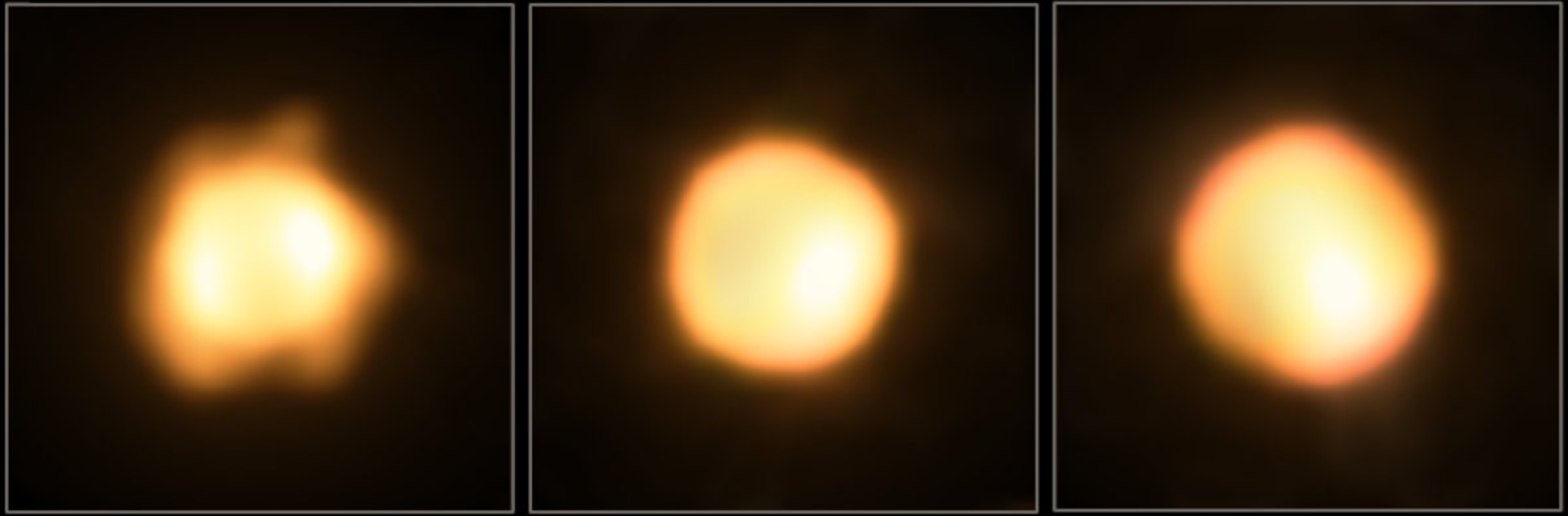
π^1 Gruis (12/17)



For the first time, granulation patterns on a star other than the Sun have been seen — using the PIONIER instrument on ESO’s VLT.

V766 Centauri

(2/16-4/17)



Epoch I
Feb-Mar 2016

Epoch II
May-July 2016

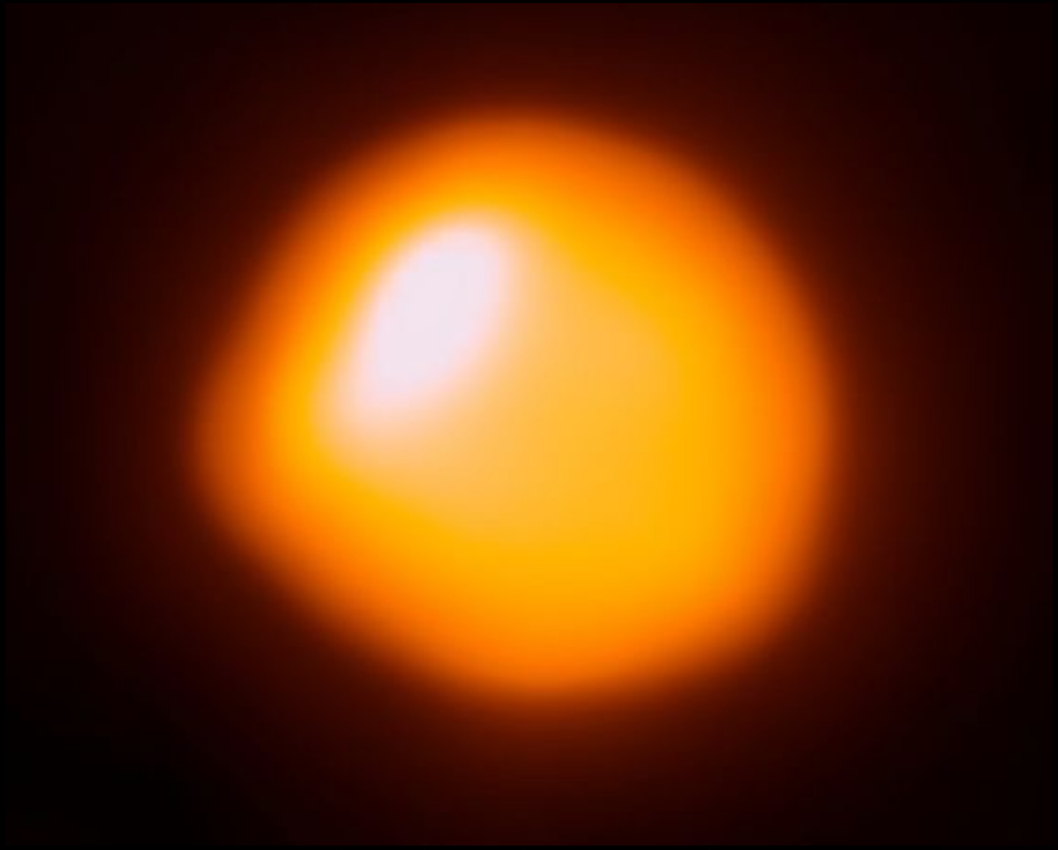
Epoch III
Feb-Apr 2017

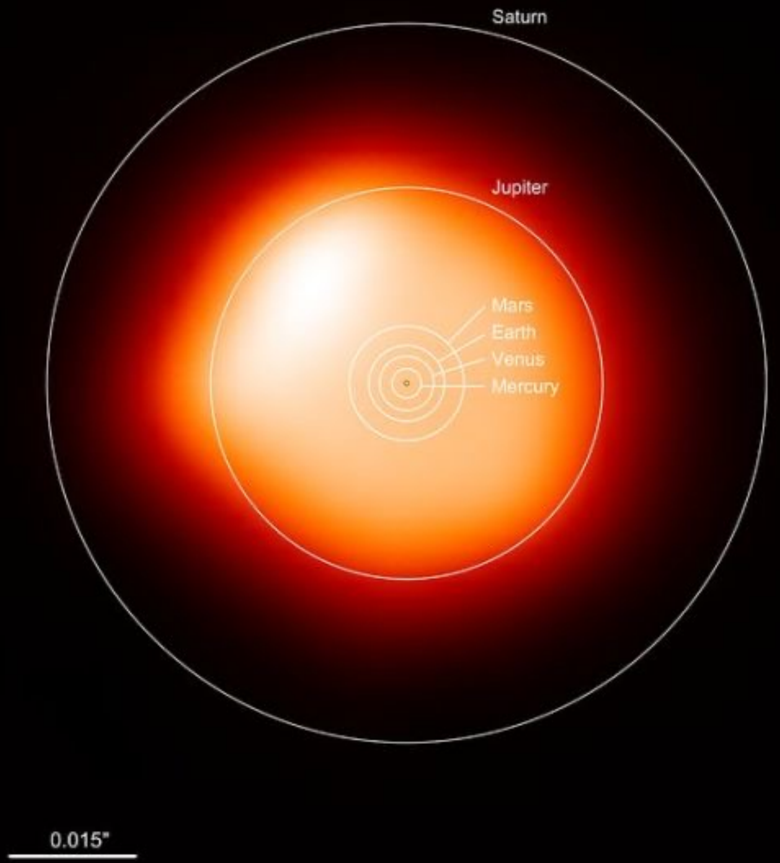
VLTI Revisits the Largest Yellow Hypergiant Ever Discovered

The Atacama Large Millimeter/submilimeter Array (ALMA)

Credit: ESO/C. Malin

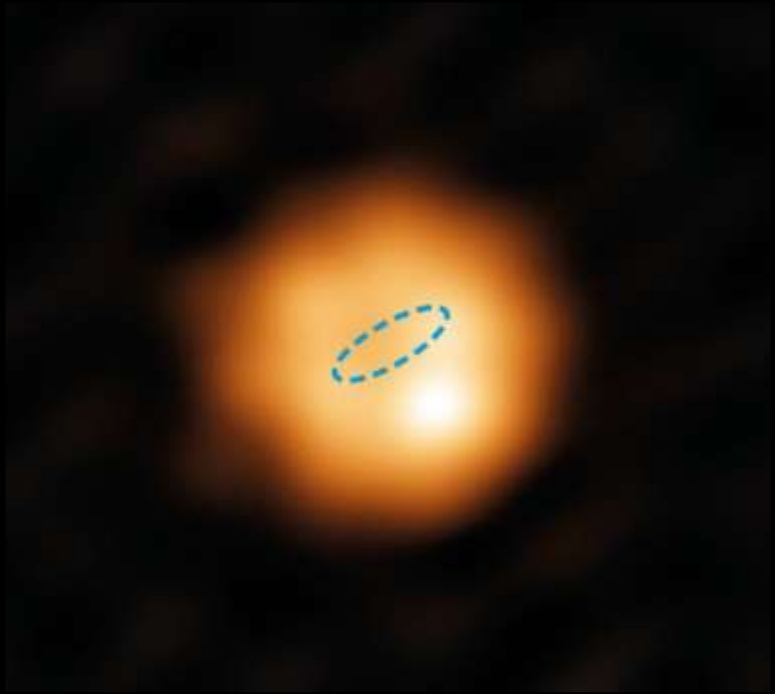
Betelgeuse (2015)





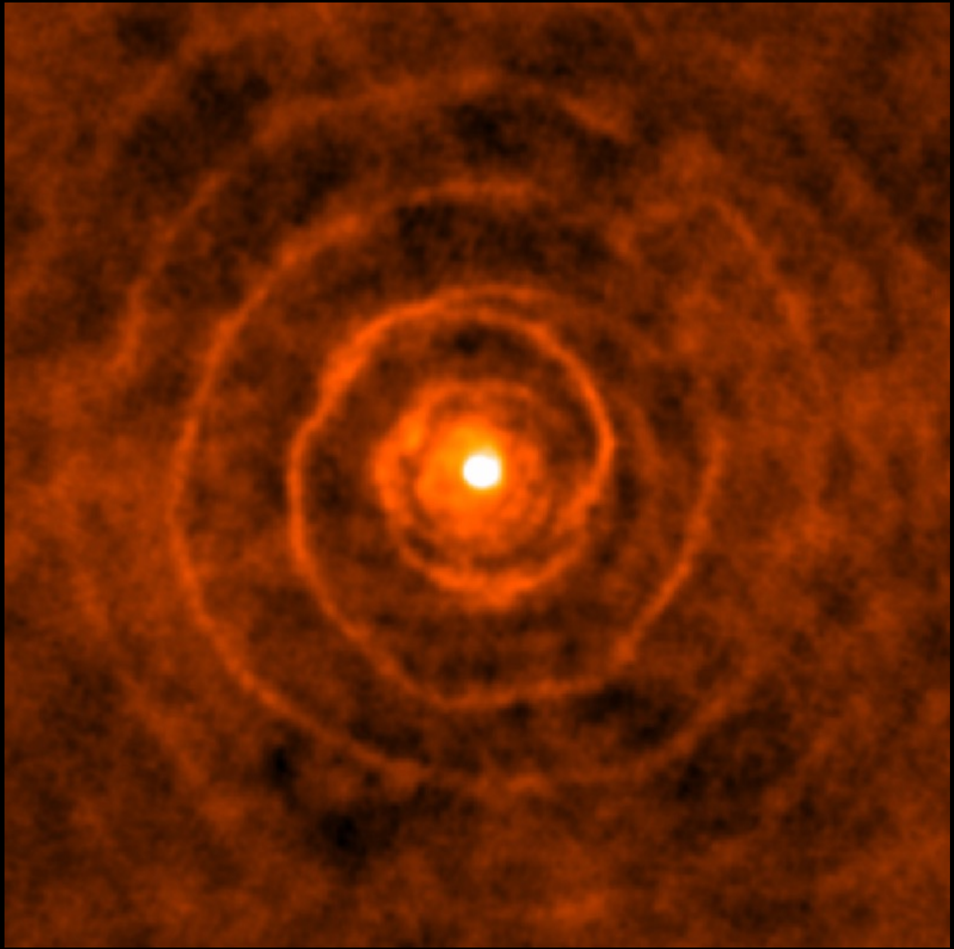
Credit: ALMA (ESO/NAOJ/NRAO)/ E. O'Gorman/P. Kervella

Evolved solar mass star W Hydrae, as seen with ALMA



LL Pegasi & Companion

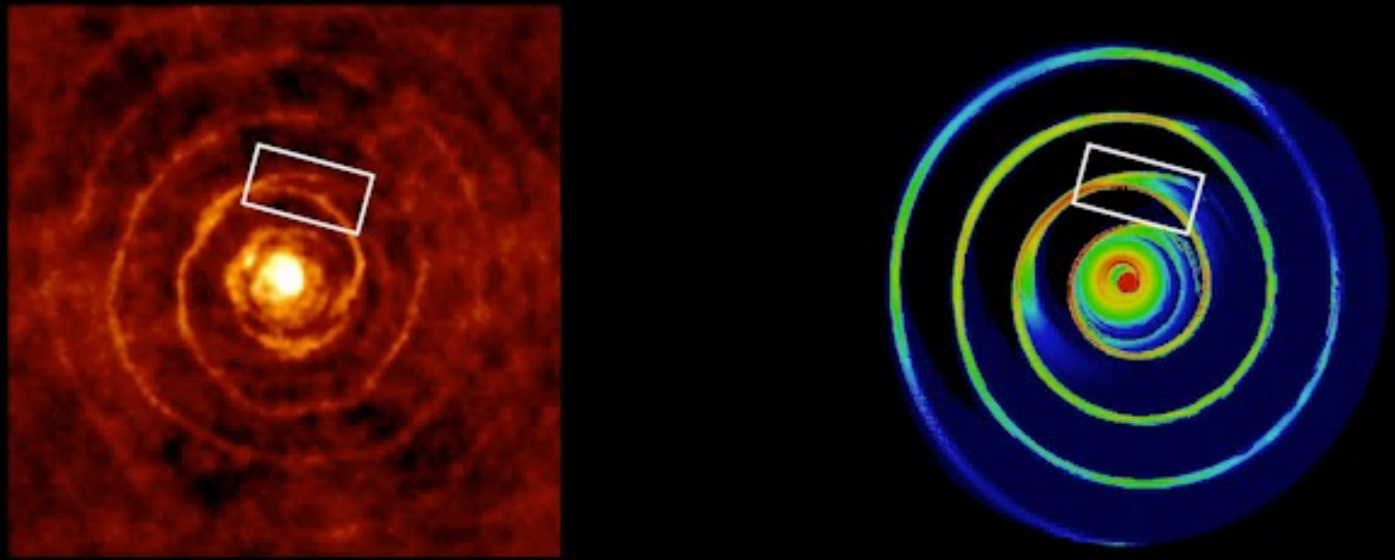
CO emission from molecular shell around the AGB star maps its mass loss



Credit: ALMA (ESO/NAOJ/NRAO)/ Hyosun Kim et al.

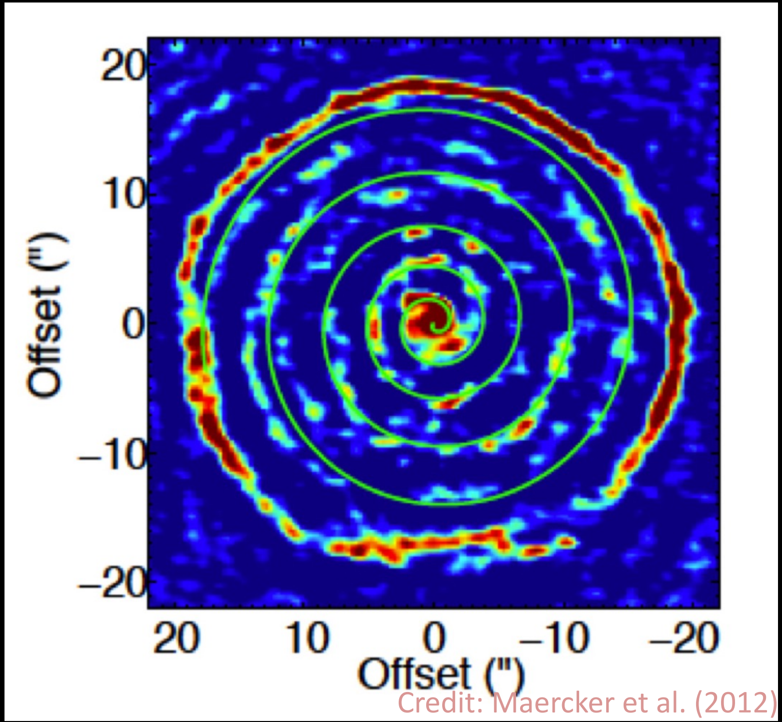
3D View of LL Pegasi

ALMA vs. Model



R Sculptoris

Curious spiral caused by companion orbiting red giant star R Sculptoris.



ALMA CO image of the molecular shell around the AGB star R Scl.

R Sculptoris

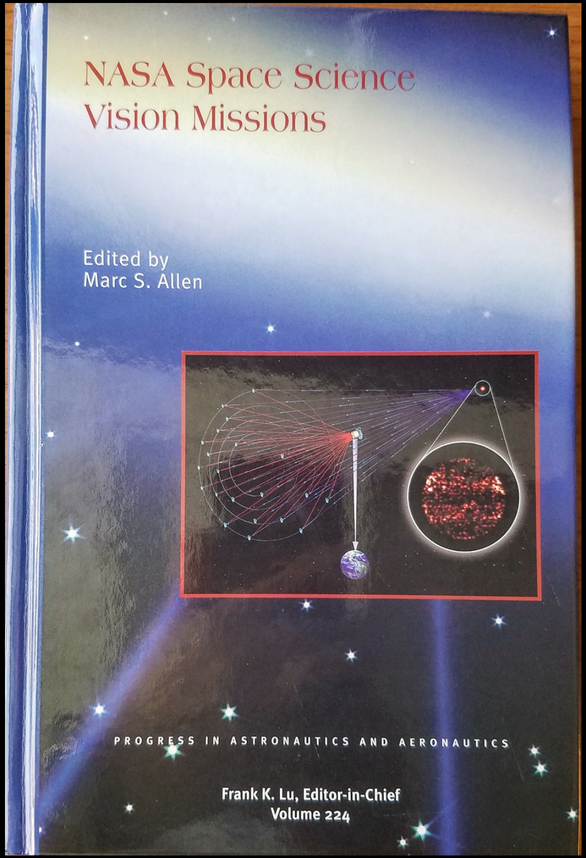
www.eso.org

The Future:
Imaging with Space-Based Interferometers

Ultimately required for extending the wavelength coverage and angular resolution needed to study the Universe in high-definition.

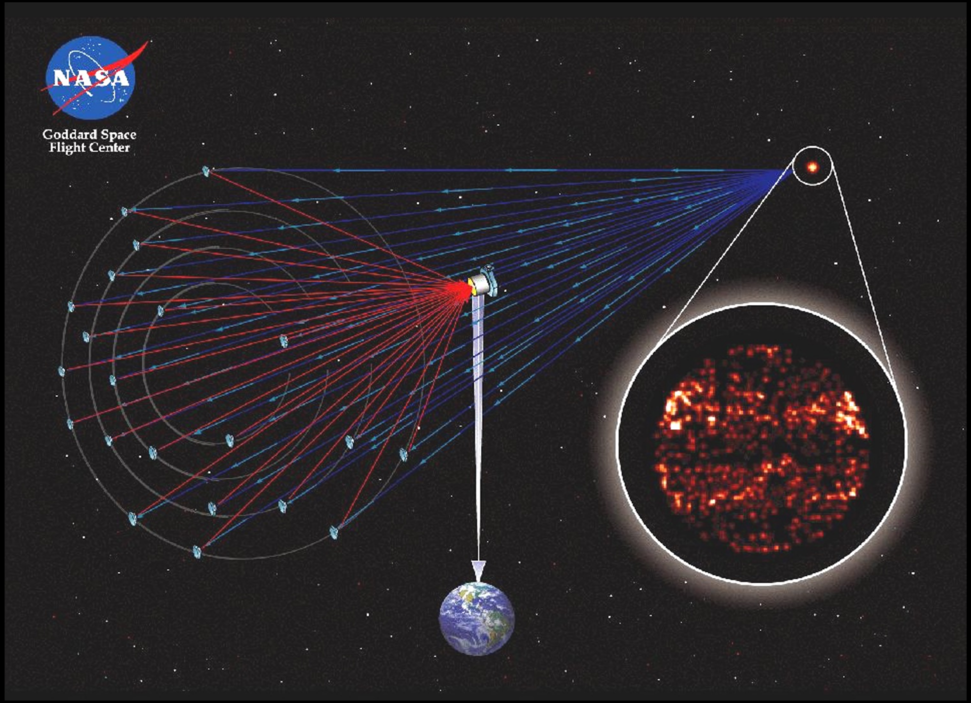
Why put Interferometers in Space

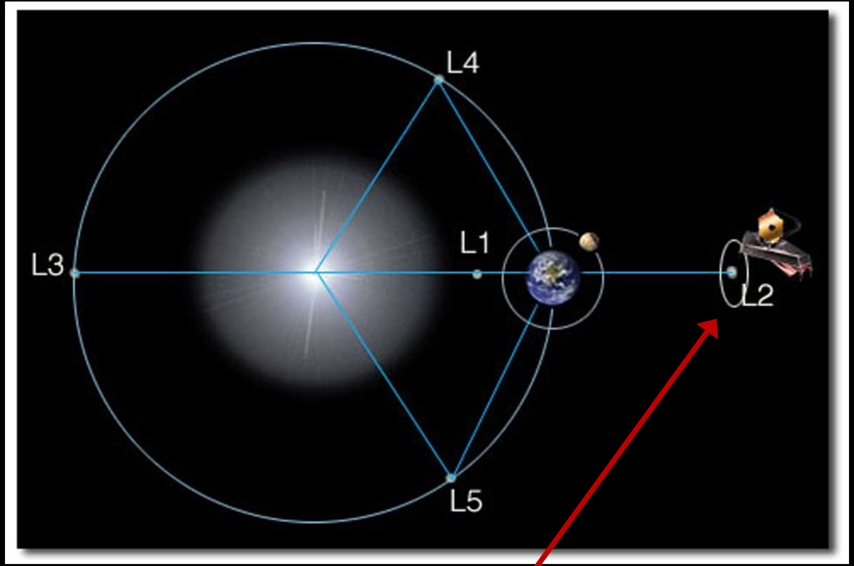
- Broader wavelength coverage
- Higher angular resolution
- Simpler architecture: no delay lines
- Observe continuously over long time periods
- Reconfigurations of array easy
- More stable environment
- No atmosphere, no turbulence
- (But more expensive/harder to access)



SI Info: https://hires.gsfc.nasa.gov/si/

SI Concept from Vision Mission (VM) Study



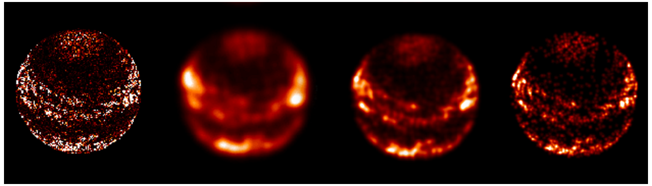


- A 0.5 km diameter UV-optical Interferometer near Sun-earth L2
- 30 primary mirrors, controlled by 1 hub; ***200x the resolution of HST***

What Will Stellar Imager See?

Solar-type star at 4 pc in CIV line

Model SIsim images

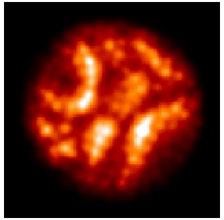


Baseline: 125m 250m 500 m

Evolved giant star at 2 Kpc in Mg H&K line

Model

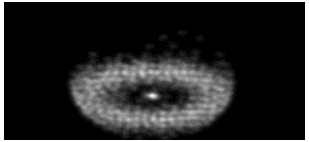
SIsim image (2mas dia)



Baseline: 500 m

SI imaging of planet forming environments: magnetosphere-disk interaction region

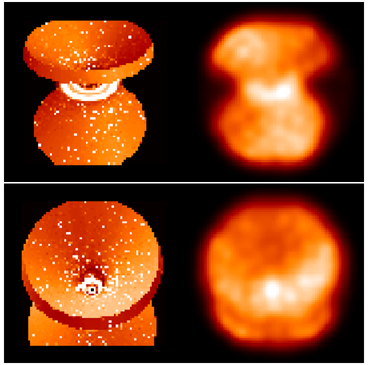
0.1 mas



SI simulation in
Ly α–fluoresced H2 lines

Baseline: 500 m

SI imaging of nearby AGN will differentiate between possible BELR geometries & inclinations



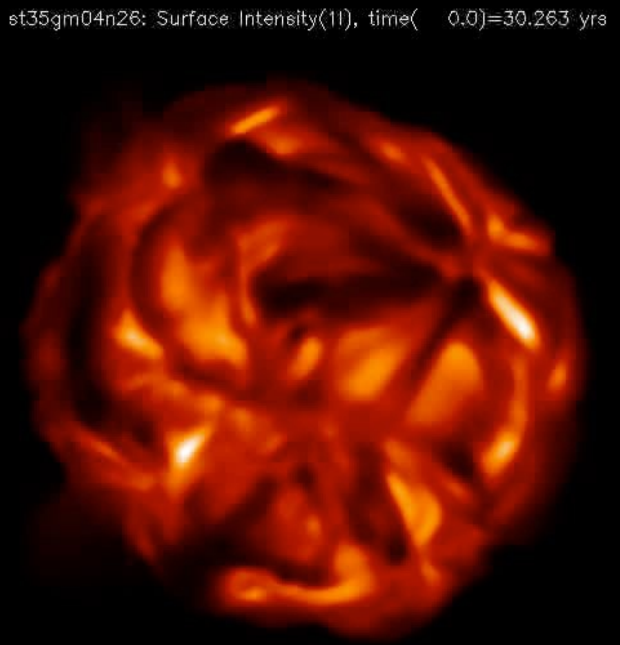
0.1 mas

model

SI simulations in CIV line
(500 m baseline)

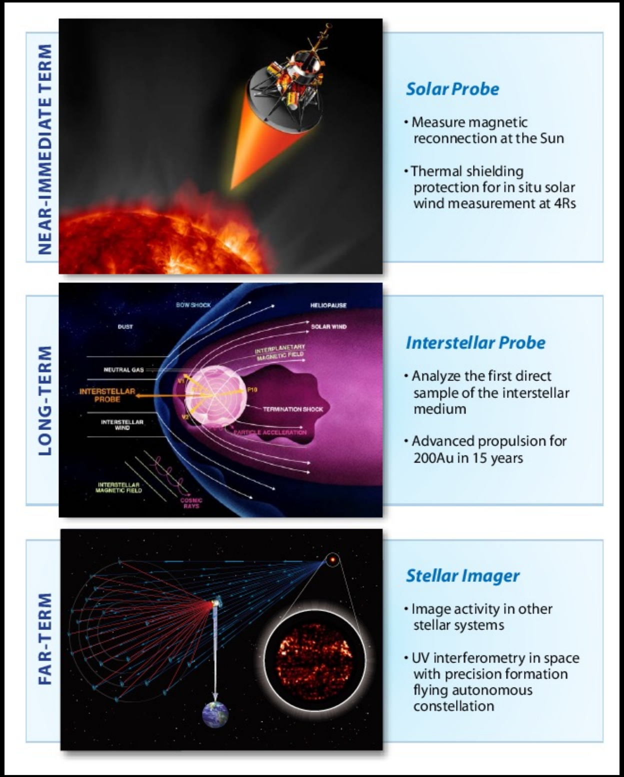
… And, SI will see motions of and *within* objects on timescales that would have astonished previous generations

- nearby stars will move across the sky as we watch
- physical processes will be directly visible
  - mass transfer in binaries
  - pulsation-driven surface brightness variation and convective cell structure in giants & supergiants
  - jets in young solar systems

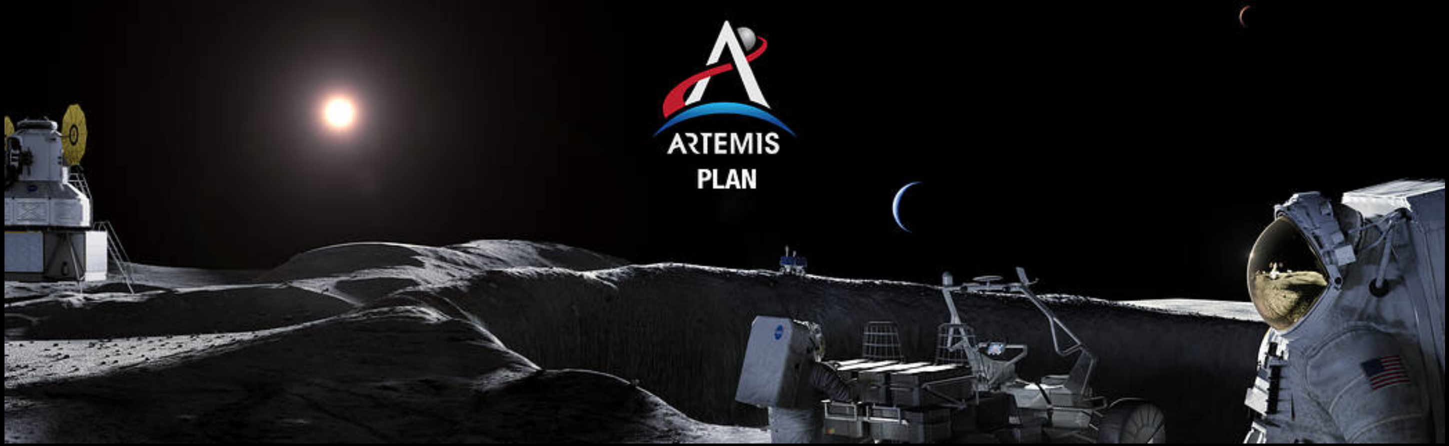


Stellar Imager *is* hard….

- Significant Technology Hurdles
  - Precision formation-flying of ~ 30 spacecraft
  - Precision metrology over multi-km baselines
  - Autonomous Control of entire system
  - How do we test on ground before launch?
- But VM Study showed possible & in 2009 SI was in the Long-Term NASA Strategic Plan
- For now, development of "Vision Missions" like SI have been slowed, but the dreams continue…



Heliophysics Division Landmark Discovery Missions



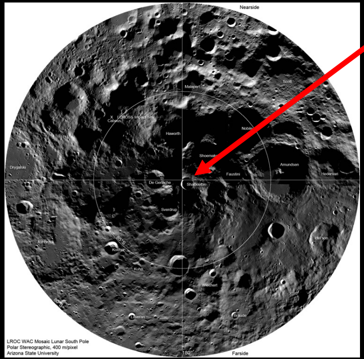
A NEW HOPE:

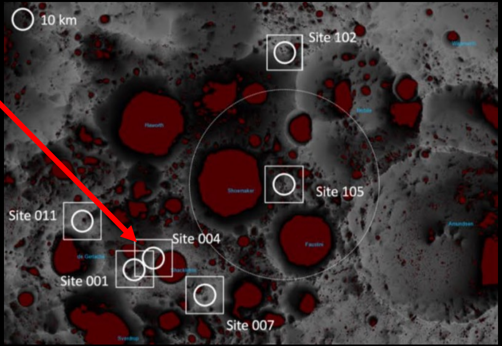
COOPERATION WITH HUMAN SPACEFLIGHT LUNAR PROGRAM

New Opportunity for Space Interferometry: Cooperation with Artemis

- The environment is changing with the Artemis Program establishing a permanent lunar human presence, starting with a base near the lunar south pole
- Even now, there is interest in small science experiments that could take advantage of the infrastructure; the scale of those opportunities will grow
- We have thus been awarded a NASA Innovative Advanced Concepts (NIAC) program to study the possibility of constructing a large-baseline, UV/optical interferometer near a human base to leverage off that infrastructure, “Artemis-enabled Stellar Imager (AeSI)”

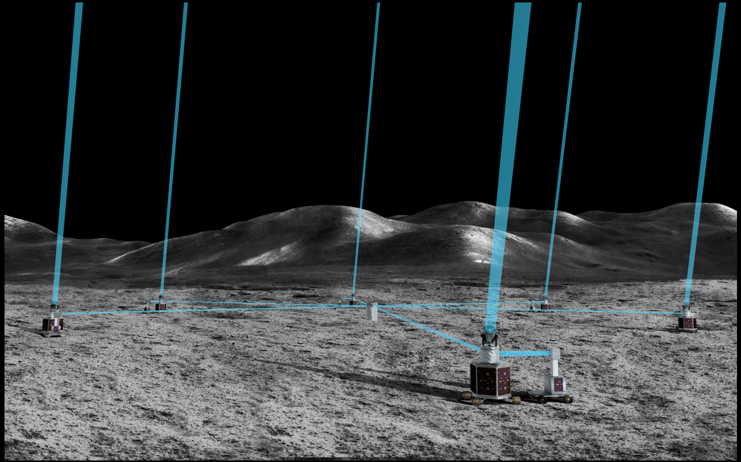
Shackleton Crater South Pole

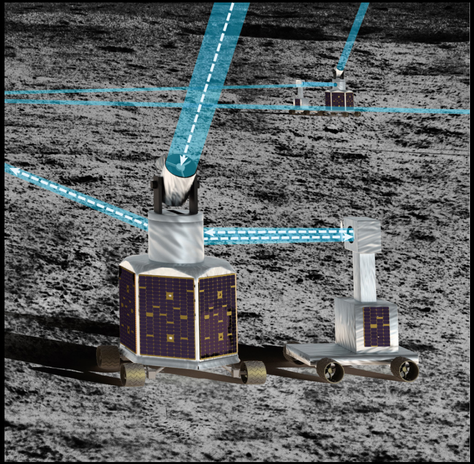




AeSI: Innovations

- **Build**: a 0.5 km baseline UV-Optical interferometer on the Moon
- **Novel technologies**: dust repellers, rovers to move delay-line optics and primary mirror stations on surface, hub to combine beams from reconfigurable stations
- **Eliminate:** the need for precision formation flying
- **Science**: support broad spectrum of science investigations
- **Timing**: can build as soon as infrastructure available on the Moon





(Britt Griswold/GSFC)

Artemis-enabled ***Stellar Imager (AeSI)***

is a UV-Optical, space-based interferometer for 0.1 milli-arcsecond spectral imaging of stellar surfaces and interiors and of the Universe in general.

It will resolve for the first time the surfaces and interiors of sun-like stars and the details of many other astrophysical objects & processes, e.g.:

Magnetic Processes in Stars

activity and its impact on planetary climates and on the origin and maintenance of life;

stellar structure and evolution

Stellar interiors

in solar and non-solar type stars

Infant Stars/Disk systems

accretion foot-points, magnetic field structure & star/disk interaction

Hot Stars

hot polar winds, non-radial pulsations, envelopes and shells of Be-stars

Cool, Evolved Giant & Supergiant Stars

spatiotemporal structure of extended atmospheres, pulsation, winds, shocks

Supernovae & Planetary Nebulae

close-in spatial structure

Interacting Binary Systems

resolve mass-exchange, dynamical evolution/accretion, study dynamos

Active Galactic Nuclei

transition zone between Broad and Narrow Line Regions;

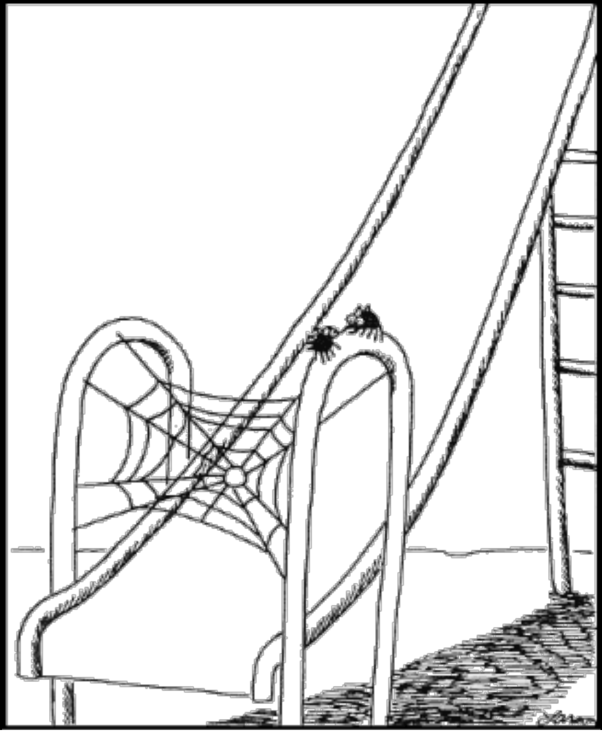
origin & orientation of jets;

distances

The Current State of Space Interferometry

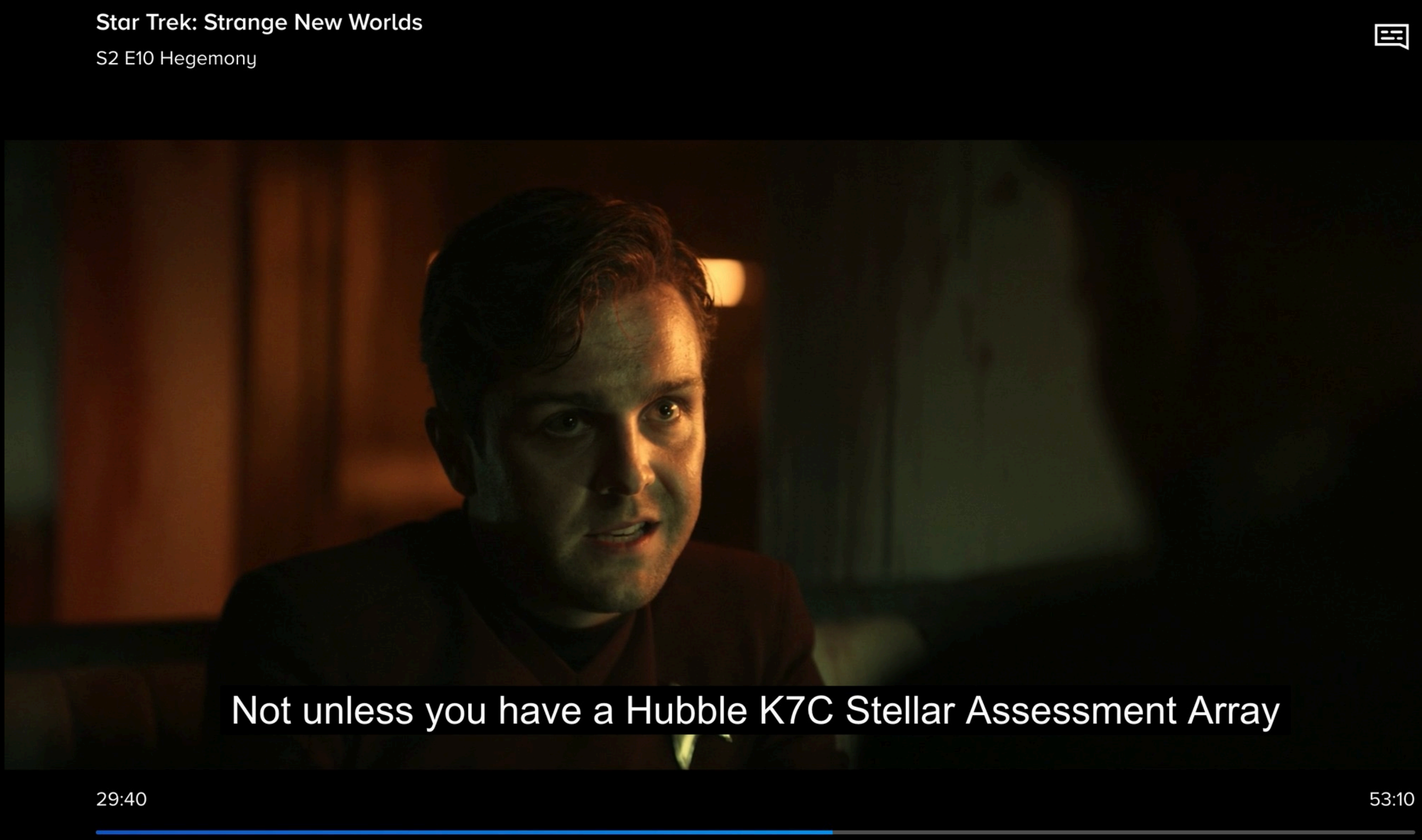
- “Yeah, that can’t be good.”
  - Sheriff Jack Carter/Eureka
- “It was the best of times,
  it was the worst of times, ...
  the spring of hope,…
  the winter of despair…
  we had everything before us, we had nothing before us…”
  - from a “Tale of Two Cities”/Dickens
- “Risk. Risk is why we’re here. It is what this (starship) interferometer is all about.”
  - James T. Kirk/ST:TOS

However…



“If we pull this off, we’ll eat like kings.”

The Farside/Gary Larson


Star Trek: Strange New Worlds
S2 E10 Hegemony
Not unless you have a Hubble K7C Stellar Assessment Array
29:40
53:10

Backup Slide

Simulated SI Images (1550 Å) for Various #Mirrors/Rotations

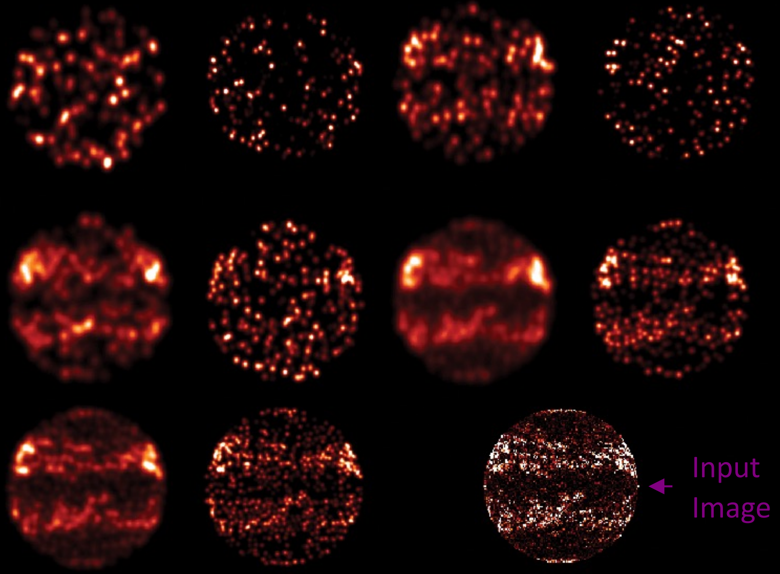
"Snapshots" (no rotations) (24 array rotations)

elements (layout)

6 (Y-array)

12 (Y-array)

30 (Golomb Rectangle)



Baselines: 250 m 500 m 250 m 500 m

Simulations calculated using SISIM, written by R. Allen/J. Rajagopal, STScI