Blowing Bubbles in the Galaxy: Chandra Detects the 1st Ever Resolved Astrosphere Around a Main Sequence G-Star

HD 61005 (aka "The Moth"), an ~100 Myr Old, "Opposite Side of the Local Bubble", G9V Disk-Hosting Star

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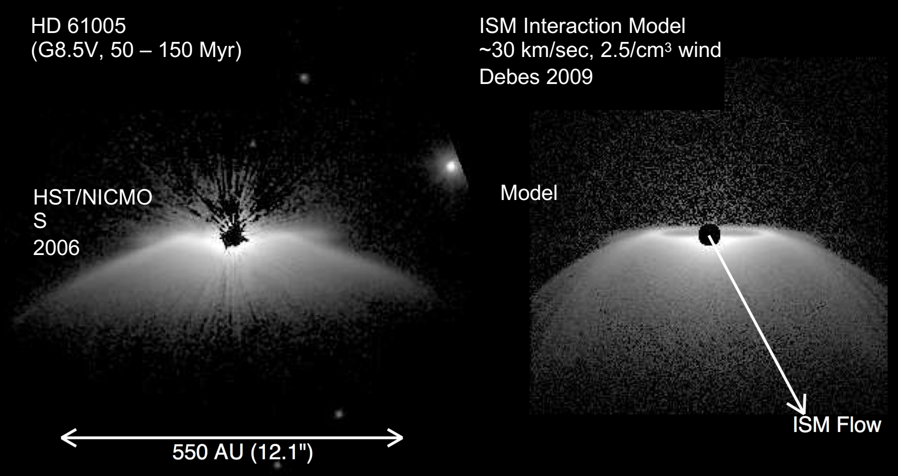
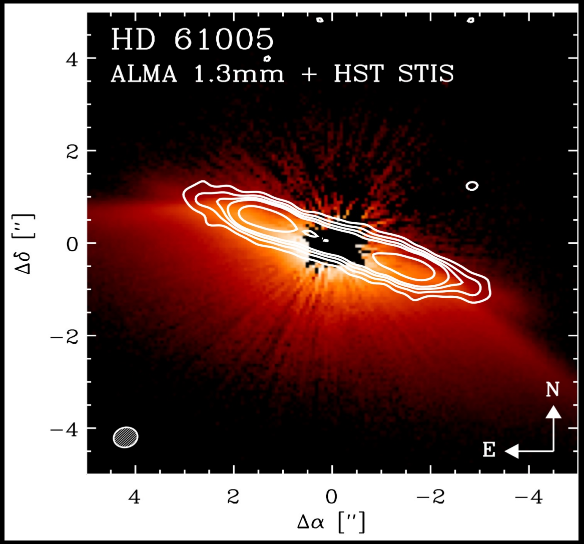
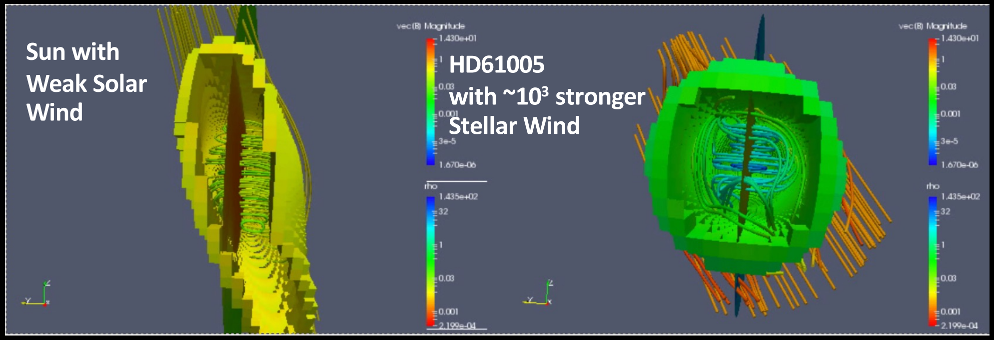


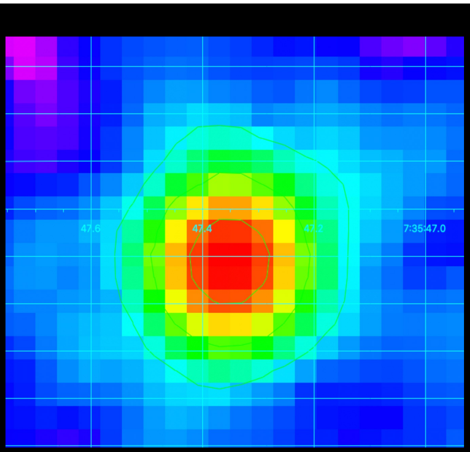
HD 61005:
Nearby (36 pc)
~100 Myr Old
G9V **Travelling**
Through a Dense
Part of the ISM
= **Our Sun** at
Zero-Age Main
Sequence

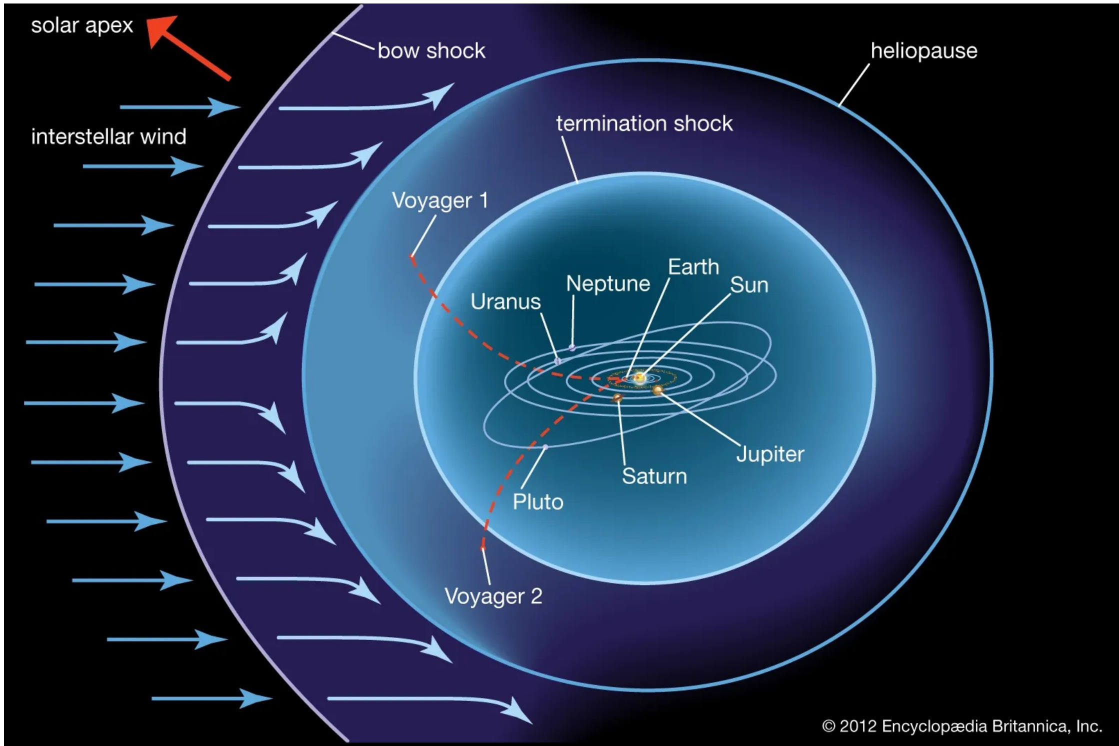




Parker 1960 Heliosphere Models

New Chandra
HD61005 X-ray
Spectral
Imaging of
Extended
Astrosphere +
Star
(Lisse+ 2024)





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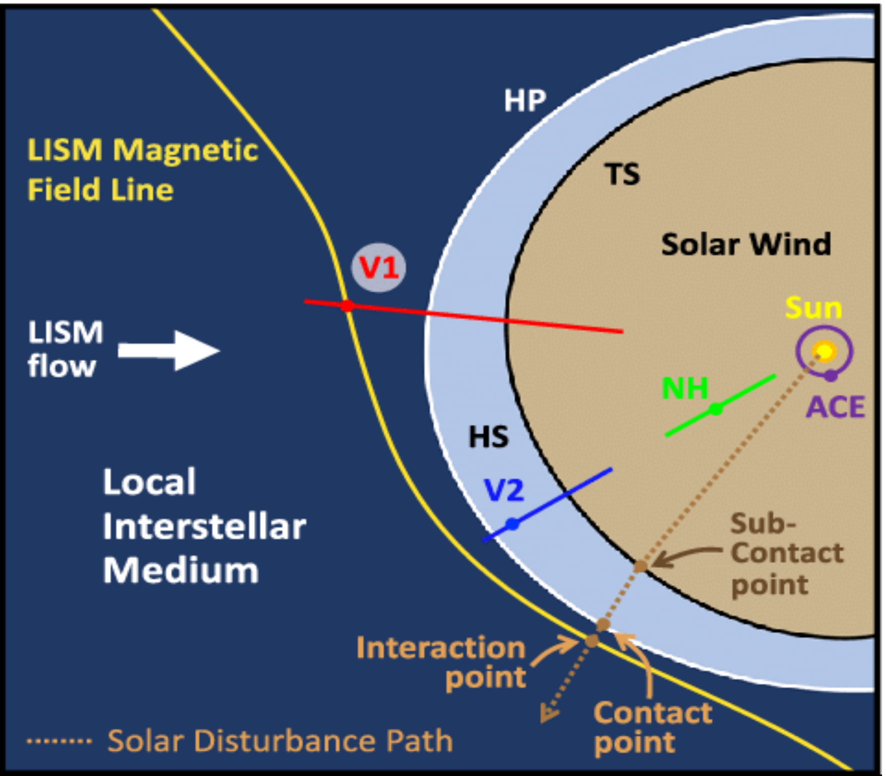
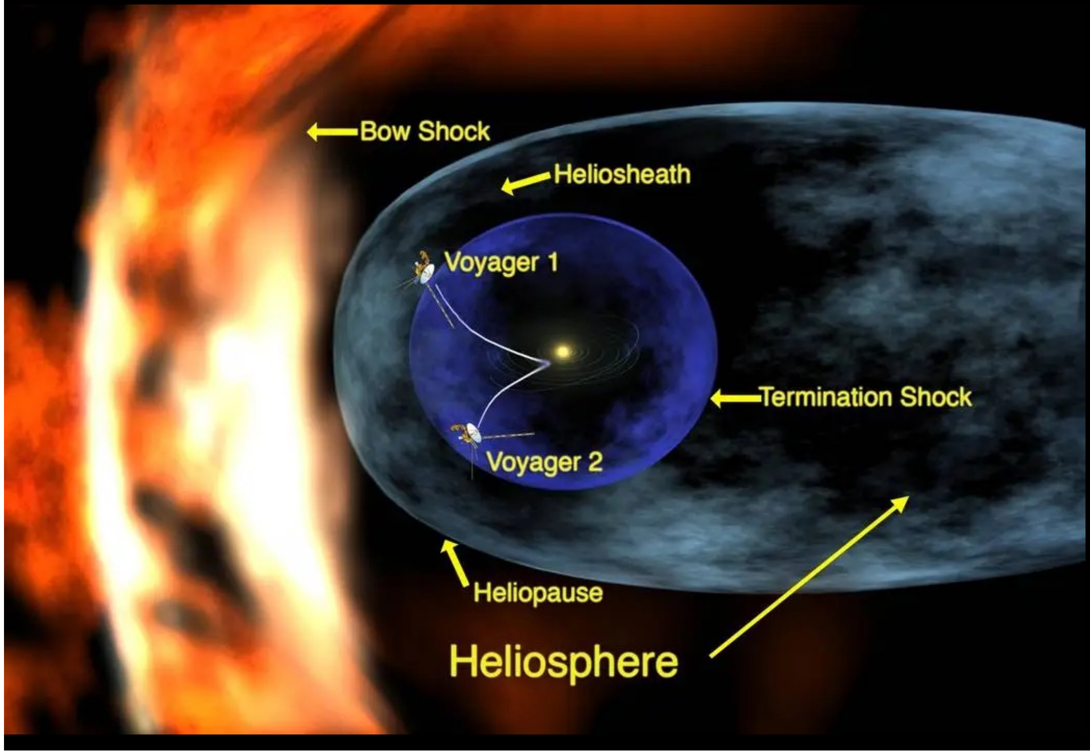
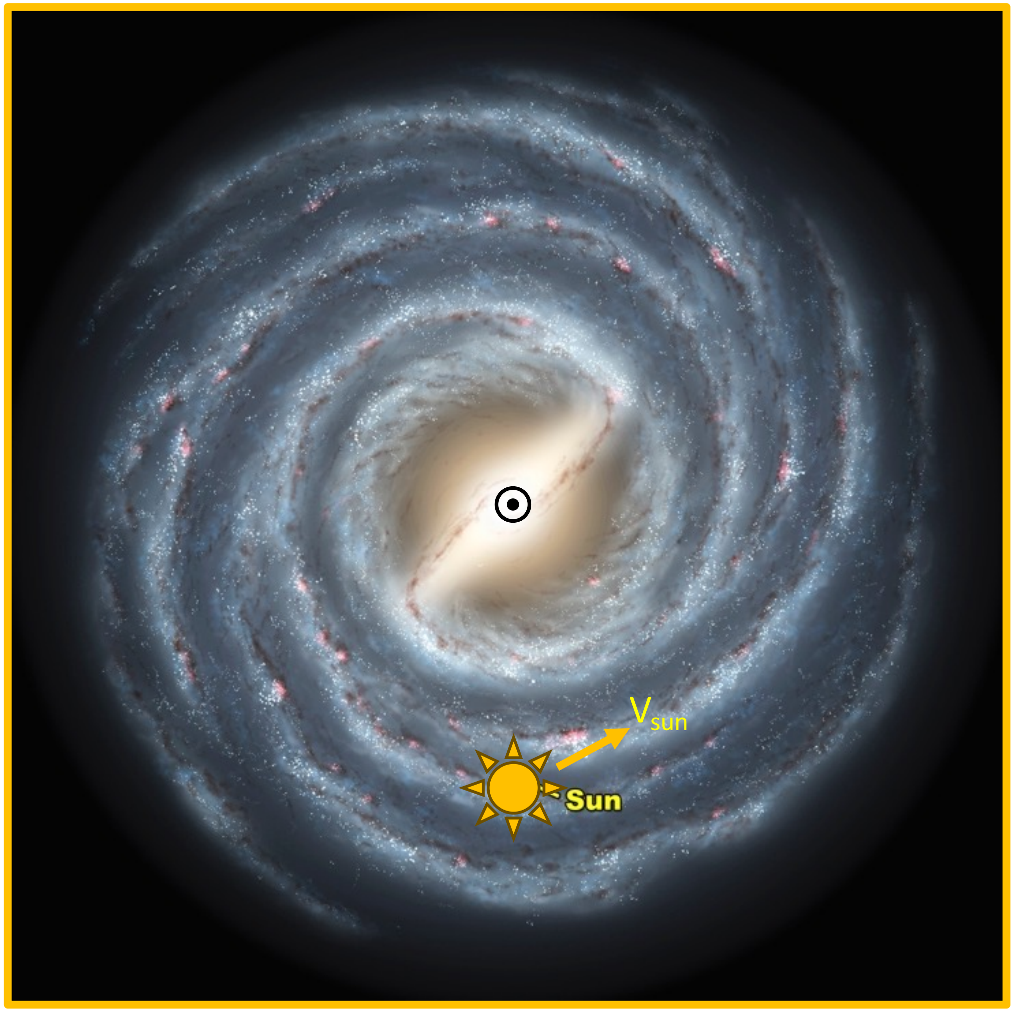
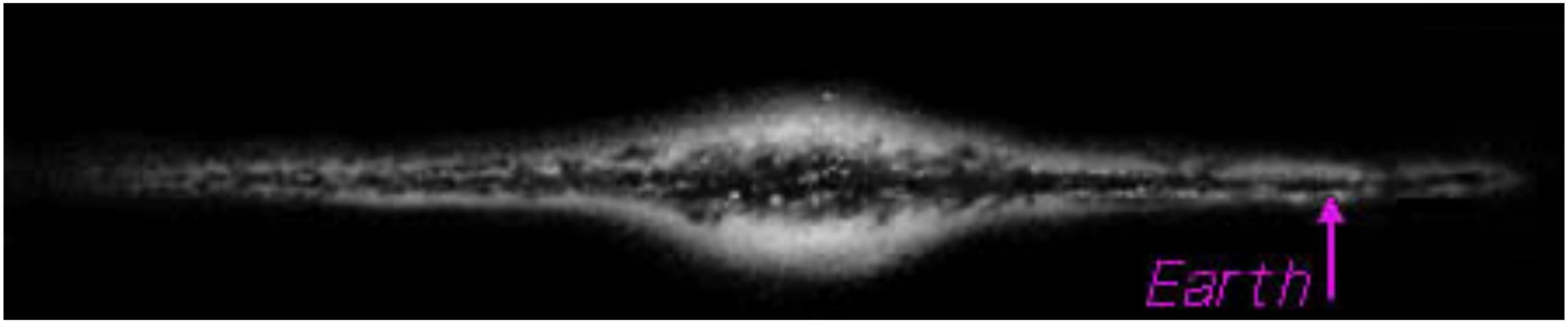




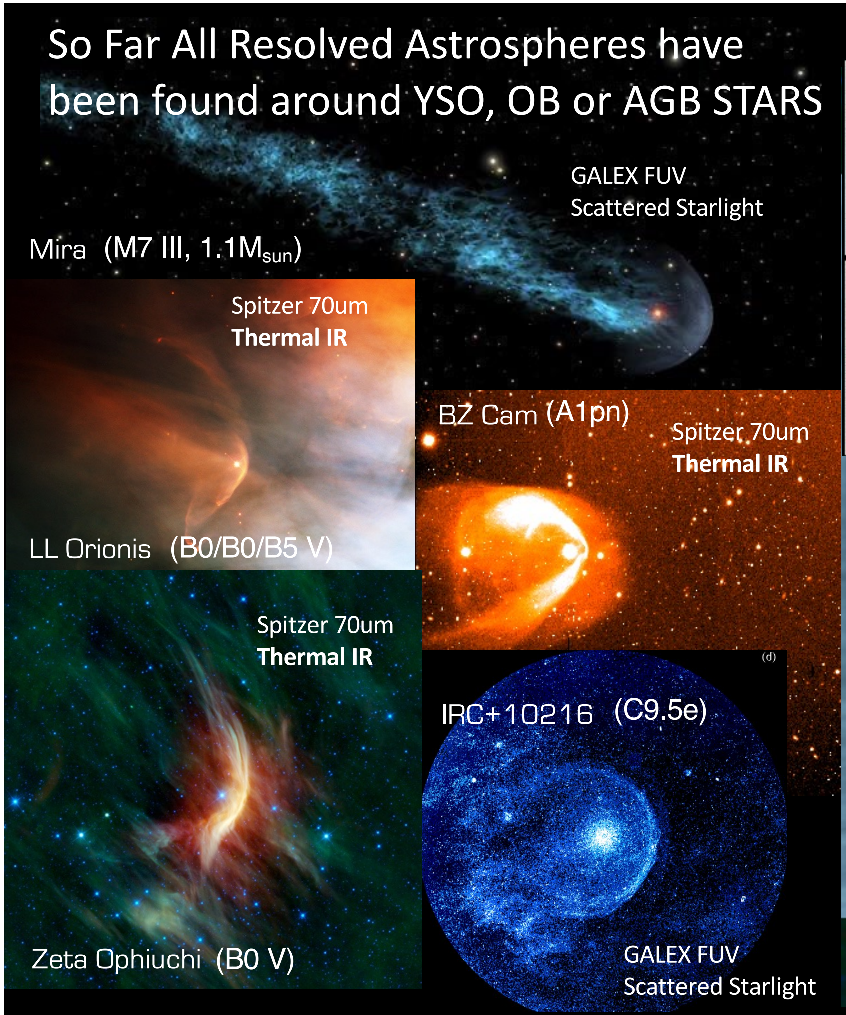
Astrospheres are bubbles blown out of the Galaxy by the pressure of a star’s stellar wind (SW). Their boundaries are defined where the pressure of the instreaming galactic material (due to the star’s orbital motion through the galaxy) equals the pressure of the outflowing SW.

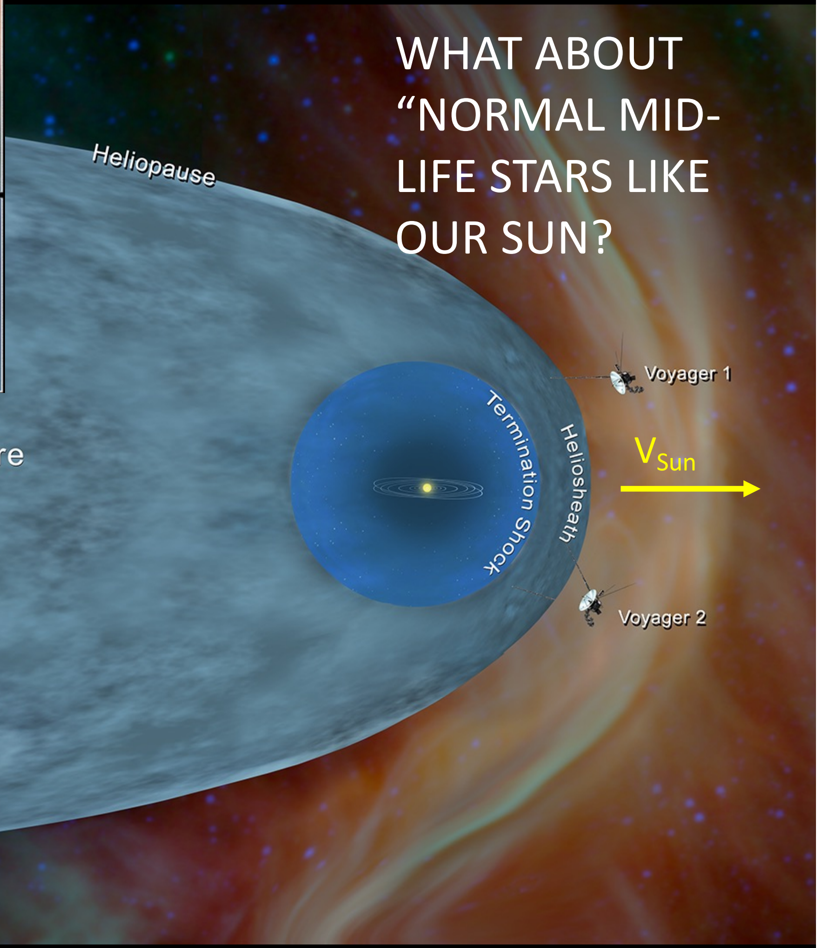


Every single one of the ~100 Billion Stars in our Galaxy blows an Astrospheric Bubble around itself, and also faces an VLISM headwind as it plows through the ISM onits orbit around the Galactic Center (v_{rel} ~ 230 km/sec, P_{rot} ~ 250 Myr).



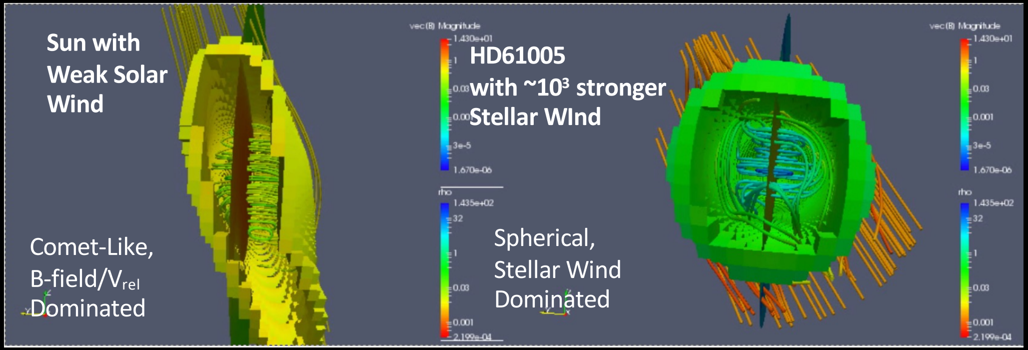
So Far All Resolved Astrospheres have been found around YSO, OB or AGB STARS





WHAT ABOUT "NORMAL MID-LIFE STARS LIKE OUR SUN?

Detecting Astrospheres Around Mid-Life, Main Sequence Stars Like the Sun is Hard!

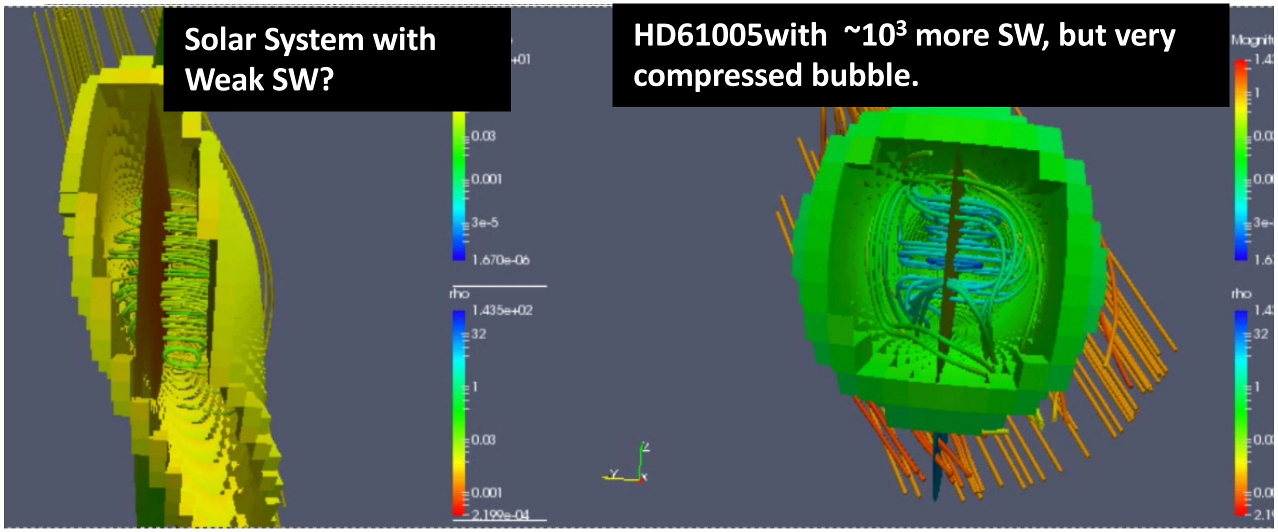


Parker's 1960 TWO Heliosphere Morphology Predictions

In order to understand what our own heliosphere is like, understanding other nearby Local Bubble system's astrospheres & astroshocks is very important - but none of the O/BAGB star systems with known resolved astrospheres are anything like G2V Sol.

Parker **1960** (yes, Parker of "Parker Solar Probe") using pressure balance

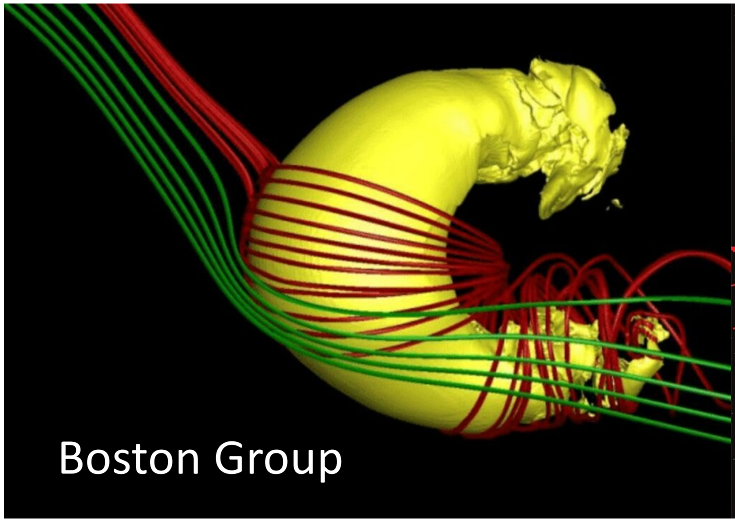
$n_{SW} * v_{SW}^2 = n_{ISM} * v_{ISM}^2 + B_{ISM}^2/4\pi + P_{ISM,thermal}$, found, with cavity radius ~10^2 AU,



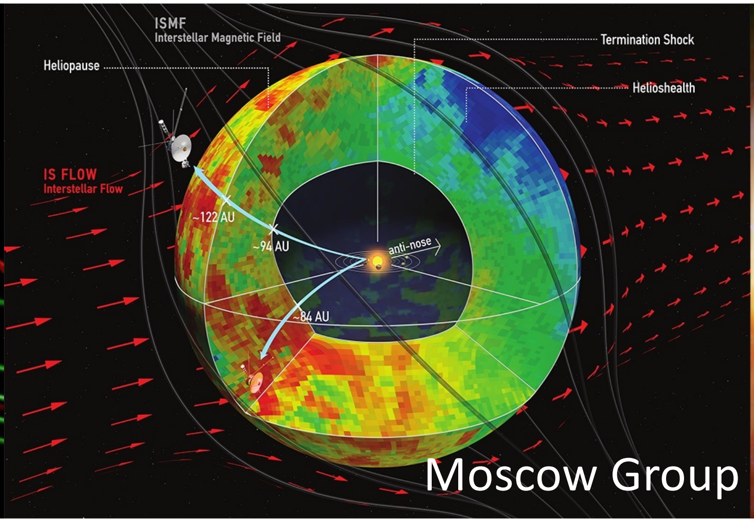
Solar System with Weak SW?

HD61005with ~10^3 more SW, but very compressed bubble.

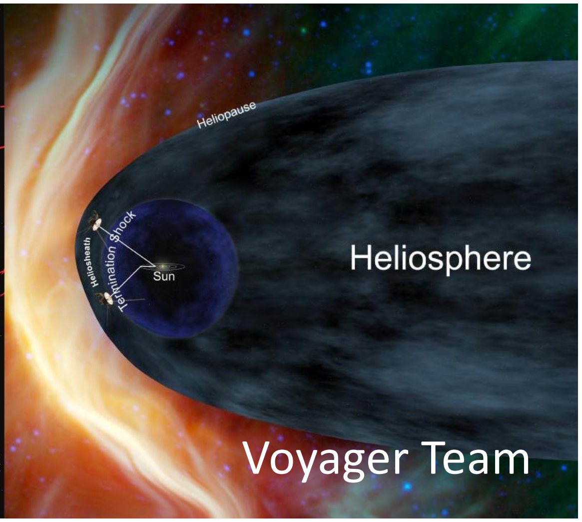
Modern Day : Current Very Different Models for Our Heliosphere's STILL Poorly Understood Morphology



Boston Group

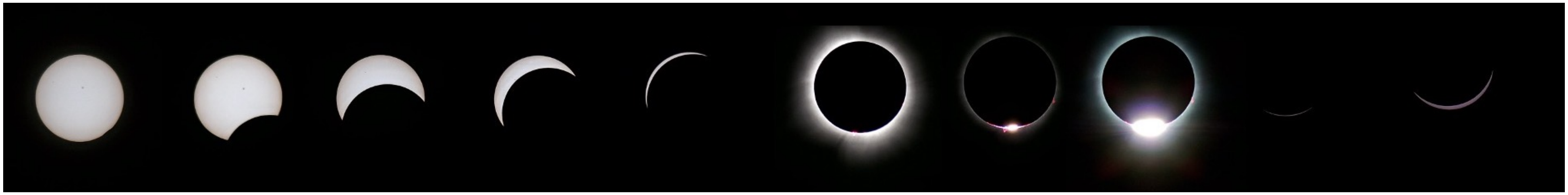


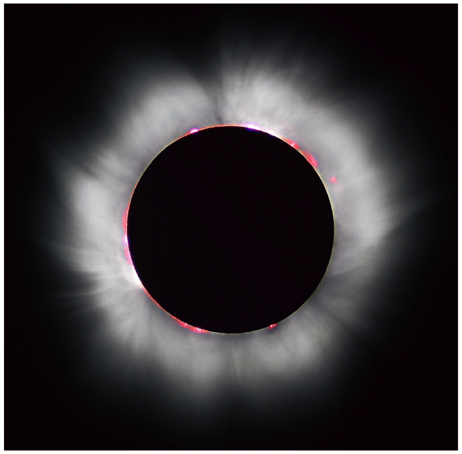
Moscow Group

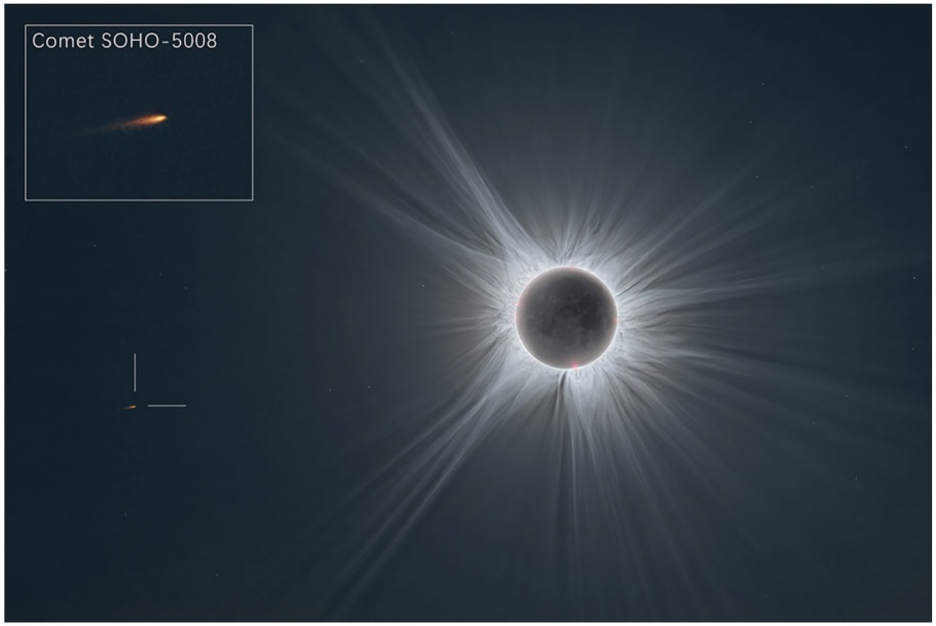


Voyager Team

One More Important Piece of Information for this Talk : Stars Have Coronae, or Ultra Hot (~1 MK), Thin Atmospheres Above Their Surfaces That Emit XUV.







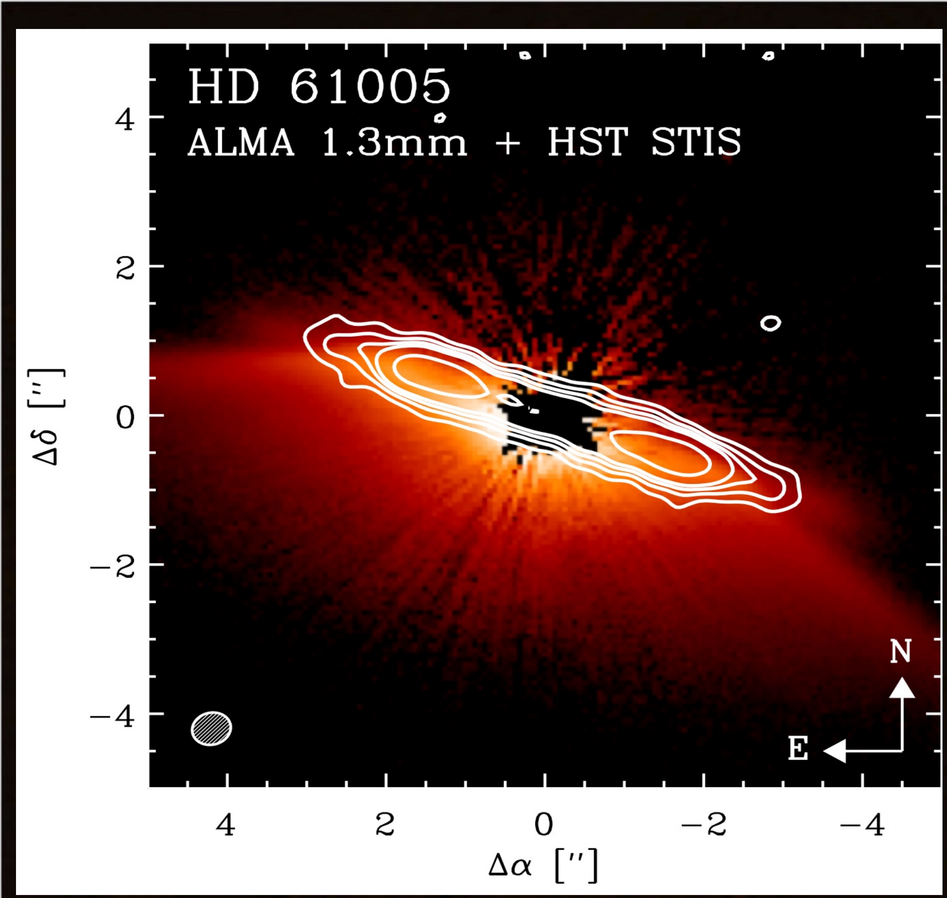
This wide-field photo of totality caught the Kreutz sungrazing comet, 5008 SOHO.
Lin Zixuan (Tsinghua University, China)

Great 08-Apr-2024 North American Solar Eclipse Directly Revealed the Actinic Light from Our Sun's MK Corona.

Observers who photographed the April 8th total solar eclipse received an unexpected bonus when totality revealed a comet diving toward the Sun, known as a *Kreutz sungrazer*. But spotting the death-diving comet required special tricks in observing and image processing.

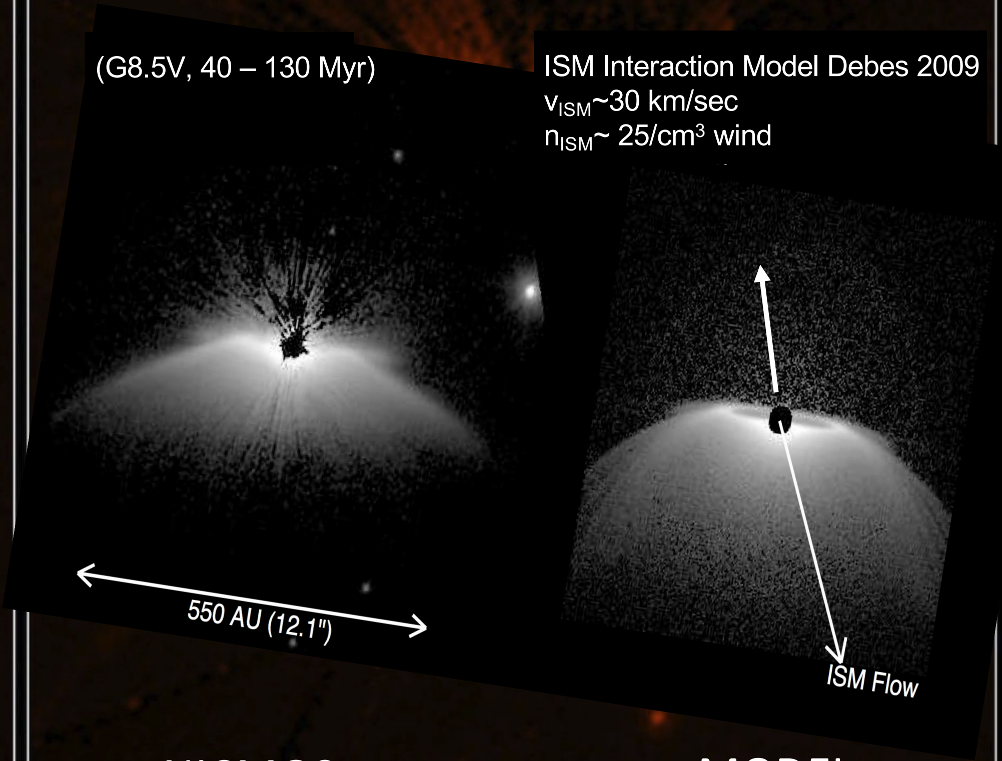
To detect Astrospheric CXE, the emission measure $\sigma_{CXE} * n_{sw} v_{sw} * n_{VLISM,neutral}$ must be large!

Enter HD61005 (aka THE MOTH)! A system harboring a Circumstellar Disk with Marked Structure due to ISM-Disk Interactions.



150 AU

Size of Neptune's Orbit



(G8.5V, 40 – 130 Myr)

ISM Interaction Model Debes 2009
v_{ISM}~30 km/sec
n_{ISM}~ 25/cm^3 wind

NICMOS

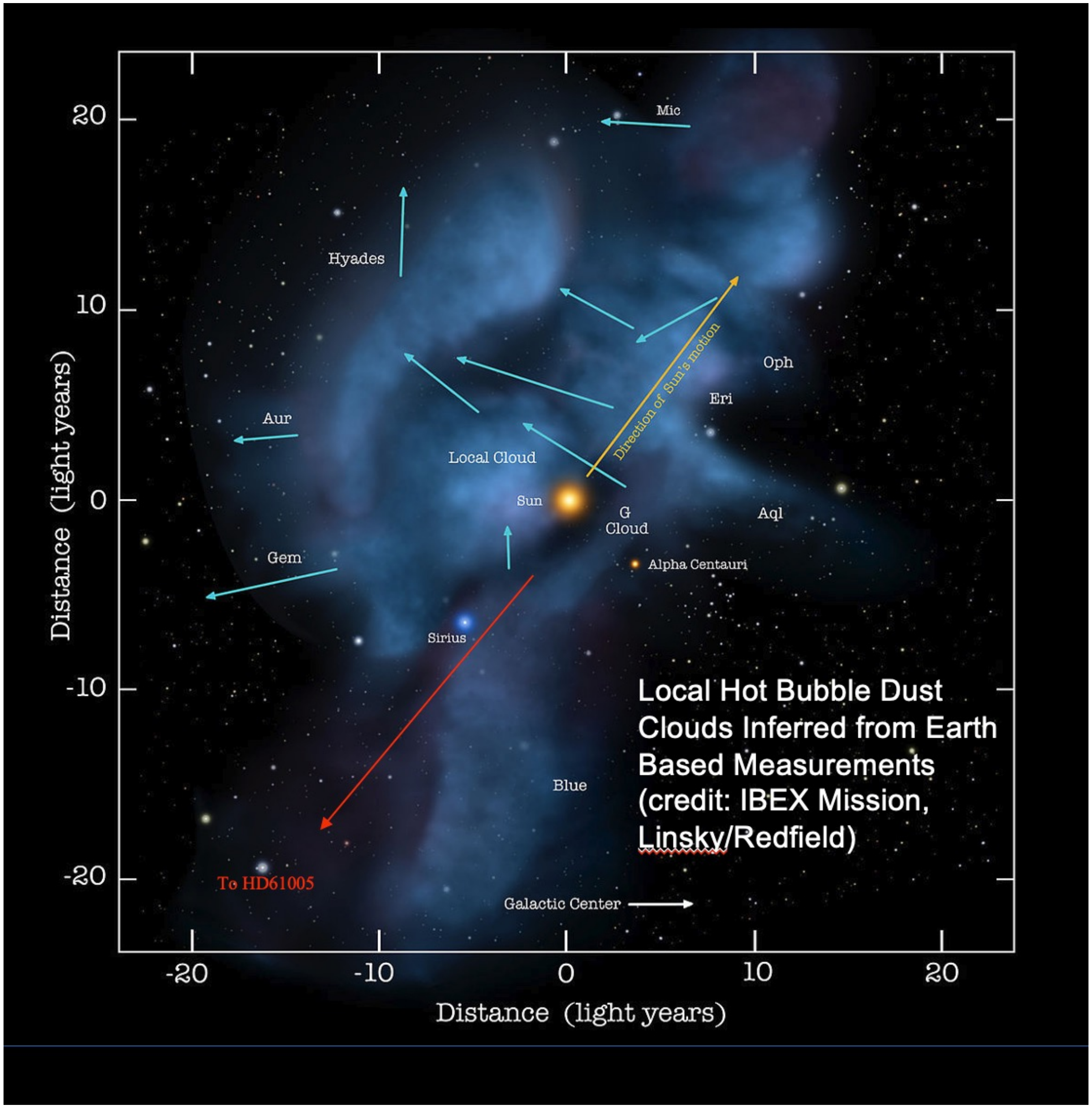
MODEL

HD 61005 Circumstellar Disk ▪ The Moth
Hubble Space Telescope ▪ NICMOS

NASA, ESA, D. Hines (Space Science Institute, New Mexico),
and G. Schneider (University of Arizona) 2007

STScI-PRC08-01

HD 61005 is located ~110 ly (36 pc) away, **on the Other Side of the Local Bubble**, in Puppis (close to the sky direction of Sirius , but ~13x farther away).



Local Hot Bubble Dust Clouds Inferred from Earth Based Measurements (credit: IBEX Mission, Linsky/Redfield)

HD61005: G9V

Mass = ~0.9 M_{sun}

Luminosity = 0.6 L_{sun}

Radius = 0.86 R_{sun}

T_{eff} = 5480 K

Age = 50 - 100 Myr old

P_{rot} ~ 5 days

d = 36 pc distant

No known planets (yet)

Bright, massive circumstellar disk observed edge-on

HD61005 was detected by ROSAT in its first ever all-sky X-ray survey (1990) with good SNR, but not included in the ROSAT Point Source Catalogue due to its strange, extended shape.

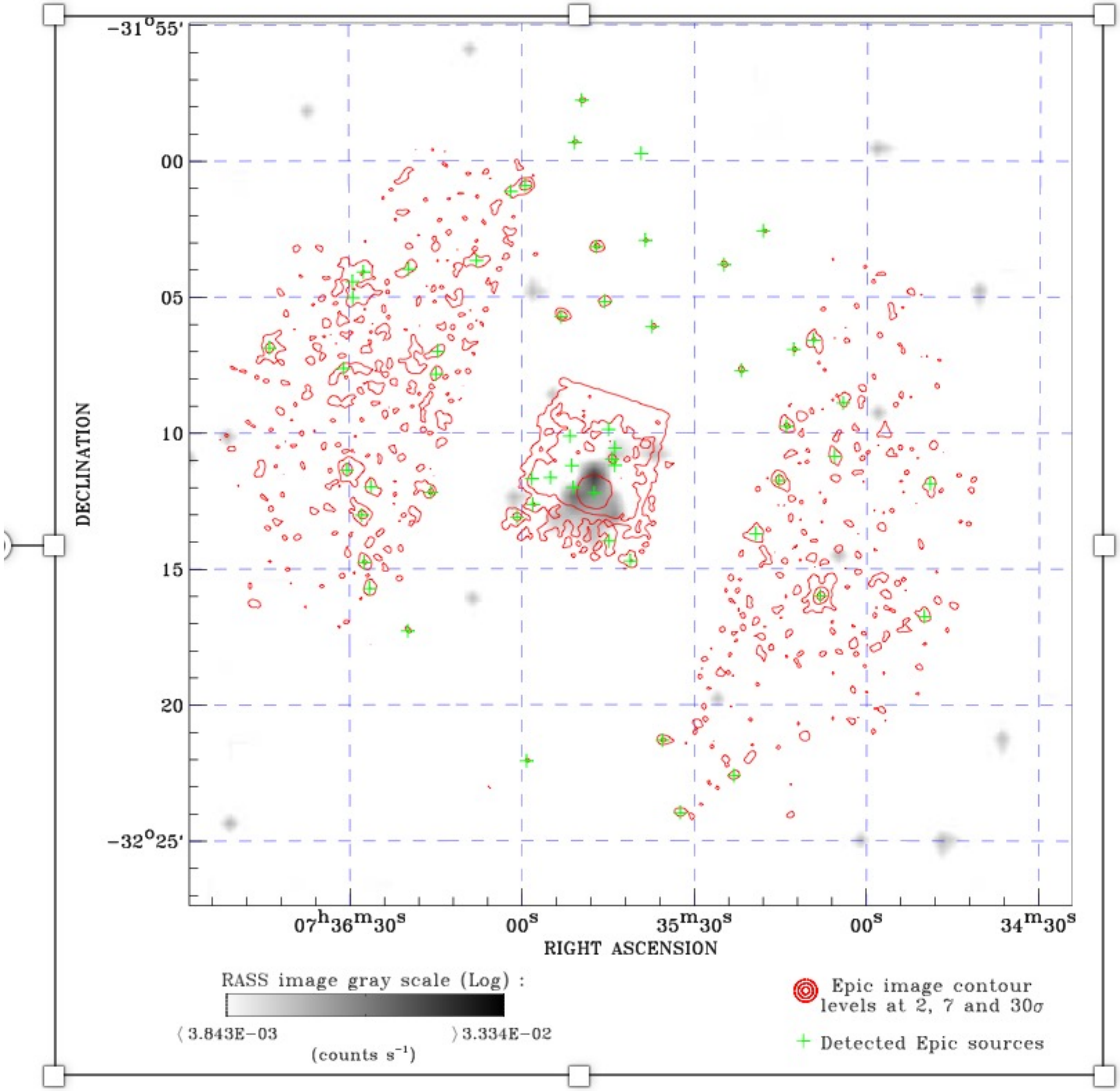
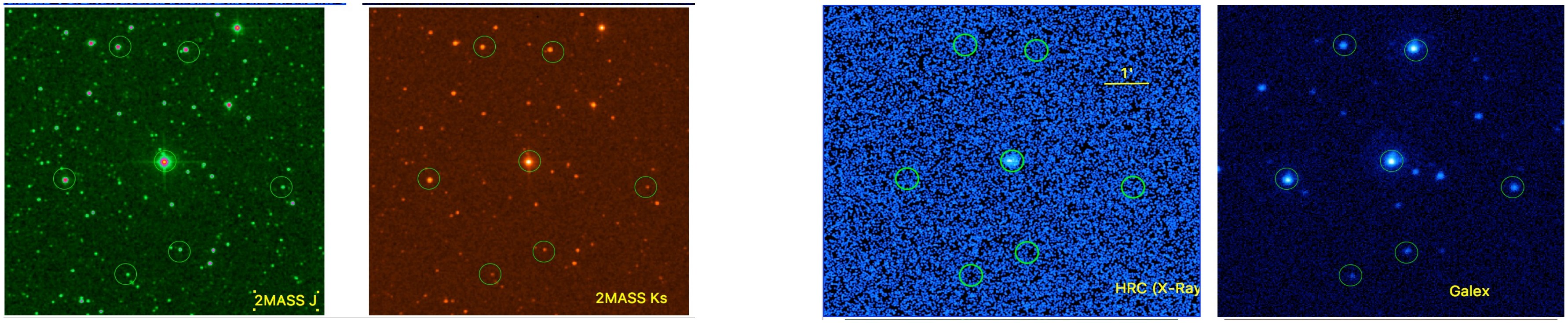
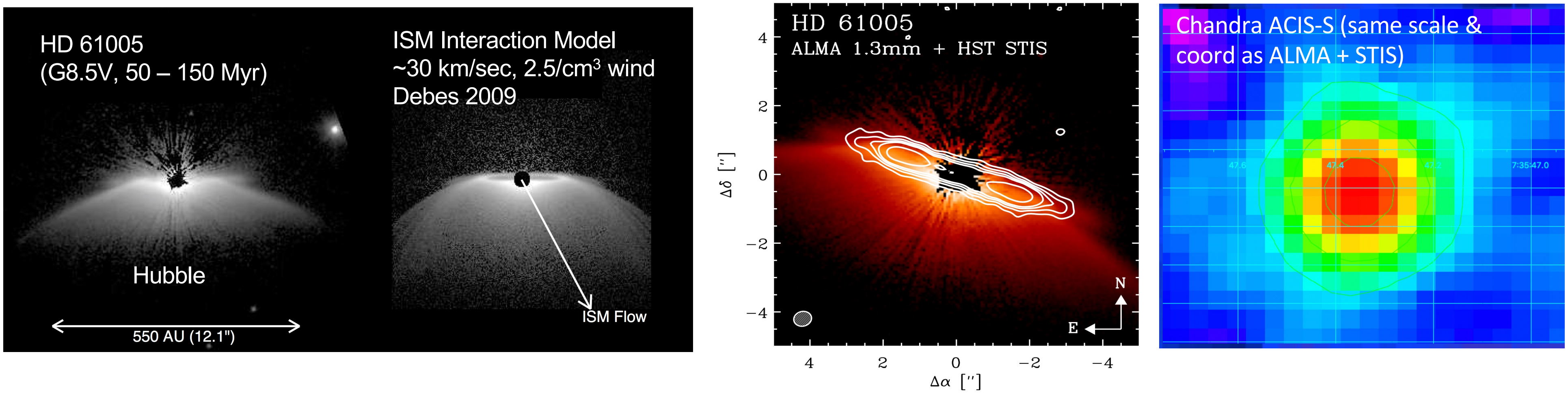


Figure 1 (b) - ROSAT All sky survey (RASS) image of the HD 61005 field (grey) with XMM EPIC contours overlaid (Red). The star is in the center of the image at (07h 35m 47s, -32d 12m 11.5s), in the clearly large and extended fan-shaped grey area. It was this reported RASS extension and asymmetry, coupled with the detection of the extended dust disk by HST (Figure 1a), that prompted the authors to observe the system with Chandra. Note also the multiple faint smudges of reported RASS flux in this image; we find evidence for a point source ~1.3’ N and W of HD 61005 in our ACIS imagery (Section 2.2).

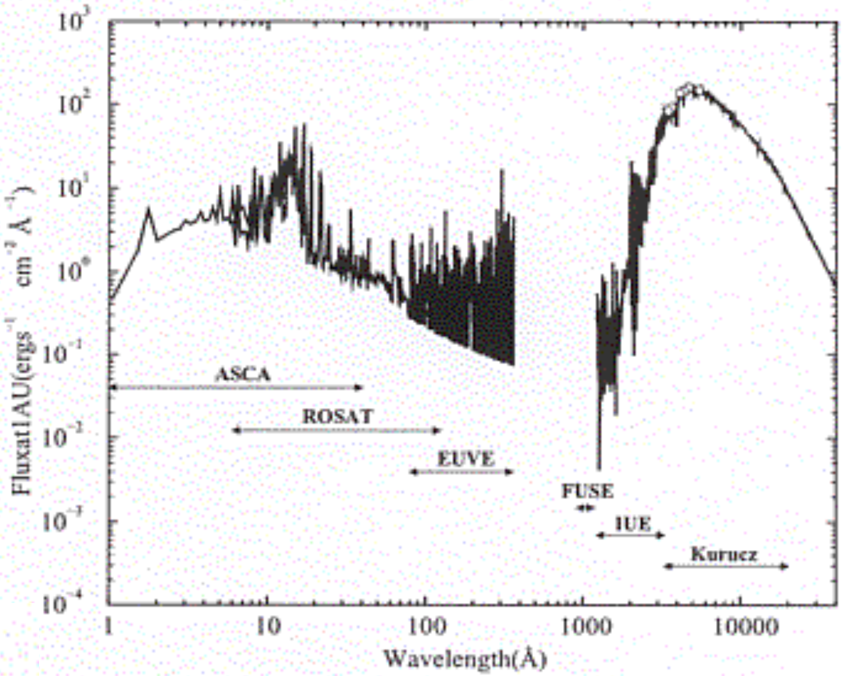


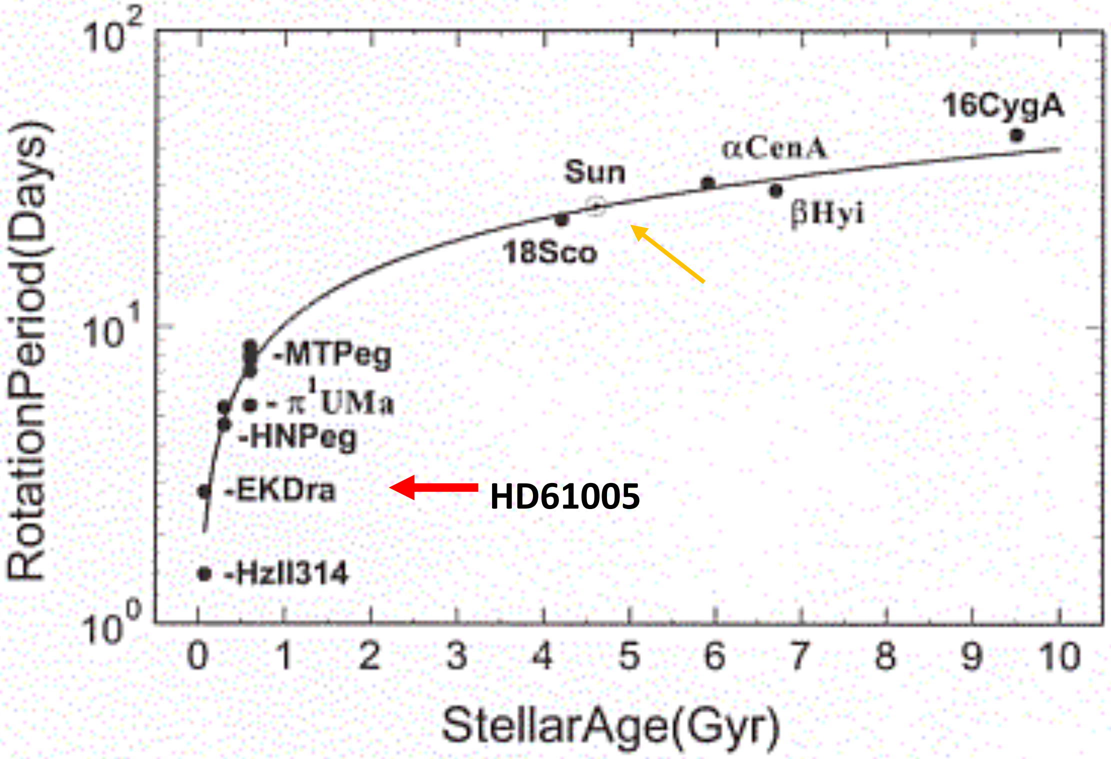
Archival 2MASS, Chandra/HRC, and GALEX observations of the HD61005 system. HD61005 is a bright, unresolved source in each band. The ~12" extent of the NICMOS NIR image could easily fit within the HWHM resolution of the shallow, off-axis ***Chandra/HRC measurement.***

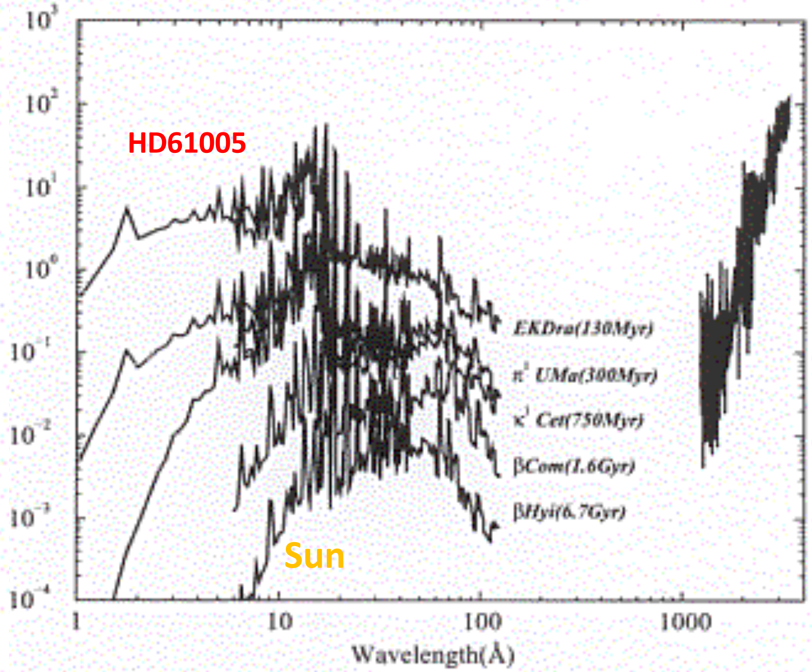


Archival HST/NICMOS near-infrared imagery of HD61005. *(left*) The swept-back wings of the outer disk can be clearly seen in contrast to the bright central flat disk running left-right in the center of the image. **Debes+ 2009 model of the system's dust structure** produced by invoking ISM wind ram pressure perturbations of circumstellar dust orbits. ***(middle)* Close up of HST/STIS (color) + ALMA imagery (contours) of HD61005 from MacGregor+ (2018),** which suggest that there are two components to the disk populated by both small micron-sized grains (HST) and larger mm-sized grains (ALMA): (1) a confined planetesimal belt between 42 and 67 AU with a rising surface density gradient and (2) an extended outer halo. **For scale, Voyager 1 has found the heliopause in our $L_x \sim 10^{27.5}$ system at ~150 AU. (right) HD61005: Chandra ACIS imagery is an ~10 pixels wide blob. For 0.5" x 0.5" pixels, this is a spherical blob about 5" in diameter, or 5" * 35 pc * 1AU/pc = 175 au across.**

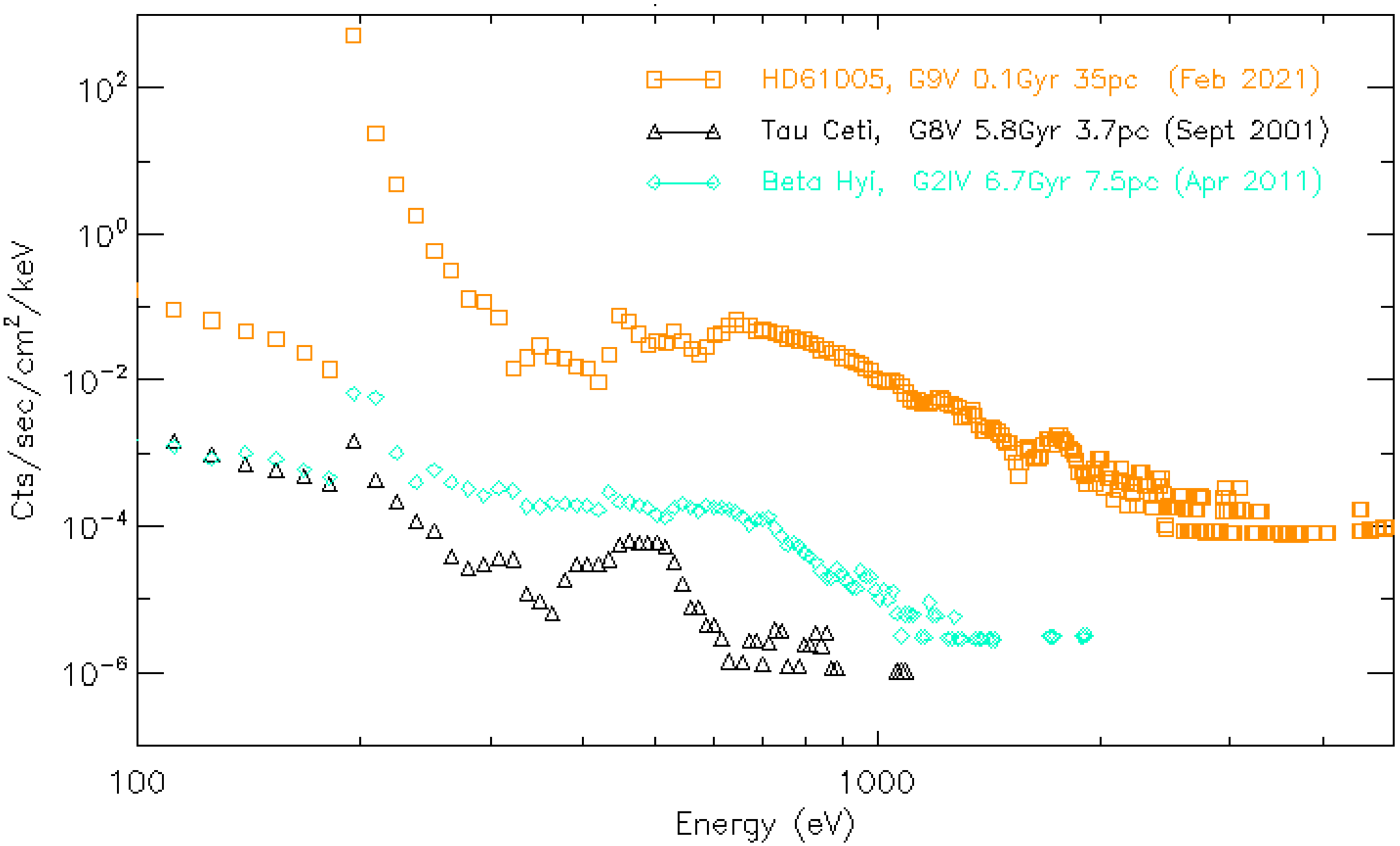
We can expect ~100 Myr Old Sun Like Stars (e.g. EK Dra, HD61005 should have hot coronae with 10^2 10^3 times more XUV flux & SW tha the Sun ("Sun in Time" study of G star Behavior by Guinan+ 2002 2007)







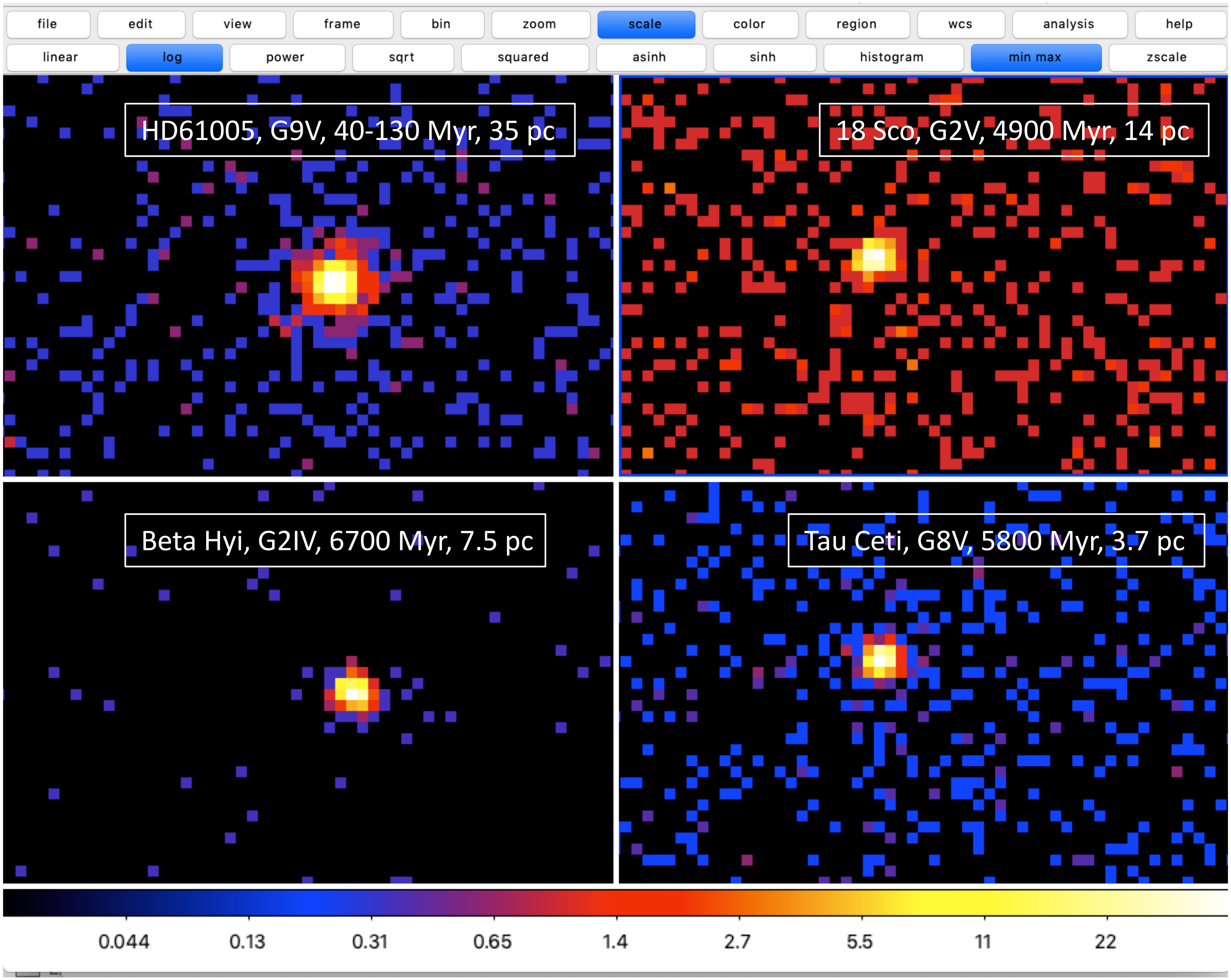
We obtained new *Chandra* ACIS-S observations of HD61005 in Feb 2021.



X-ray spectra for HD61005, Tau Ceti and Beta Hyi after correction for total on-target integration time, distance, and ACIS-S Effective Collecting Area (t).

=> ~0.1 Gyrs HD61005 is 2-3 orders of magnitude more luminous in the X-ray than 6-8 Gyrs old Beta Hyi & Tau Ceti, as predicted.

HD61005 is clearly extended in our imagery vs. *Chandra* archival images of other Sun-like G-stars.

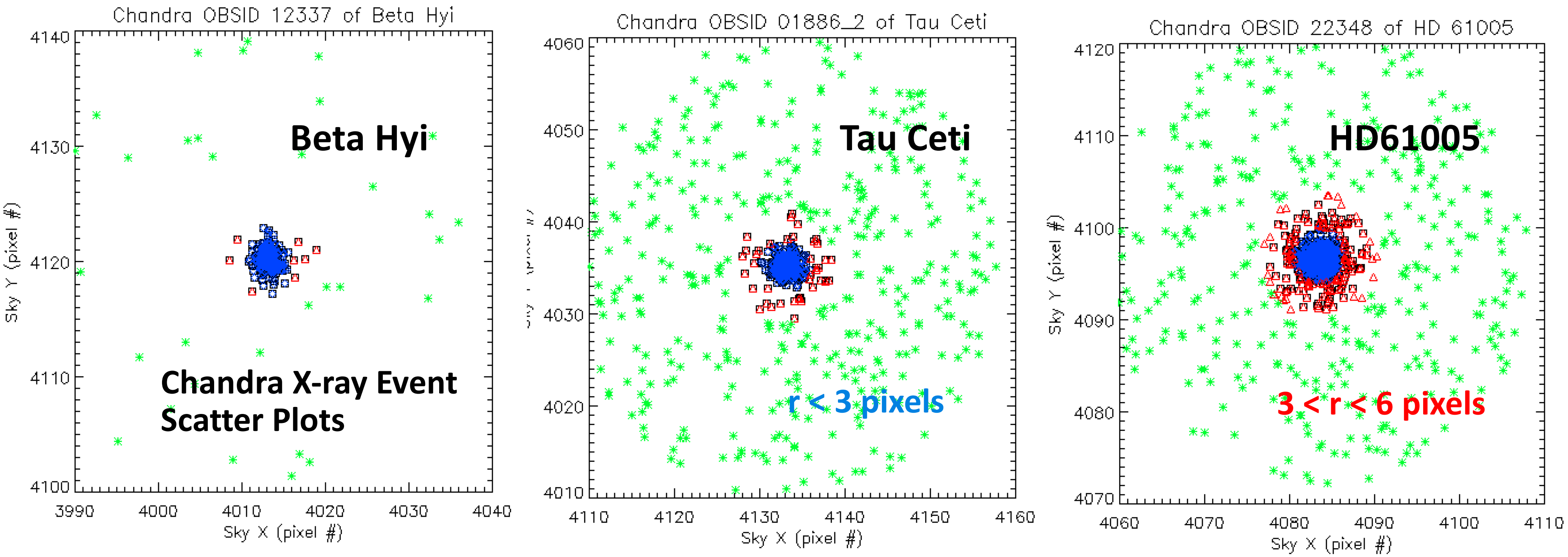


HD61005, G9V, 40-130 Myr, 35 pc

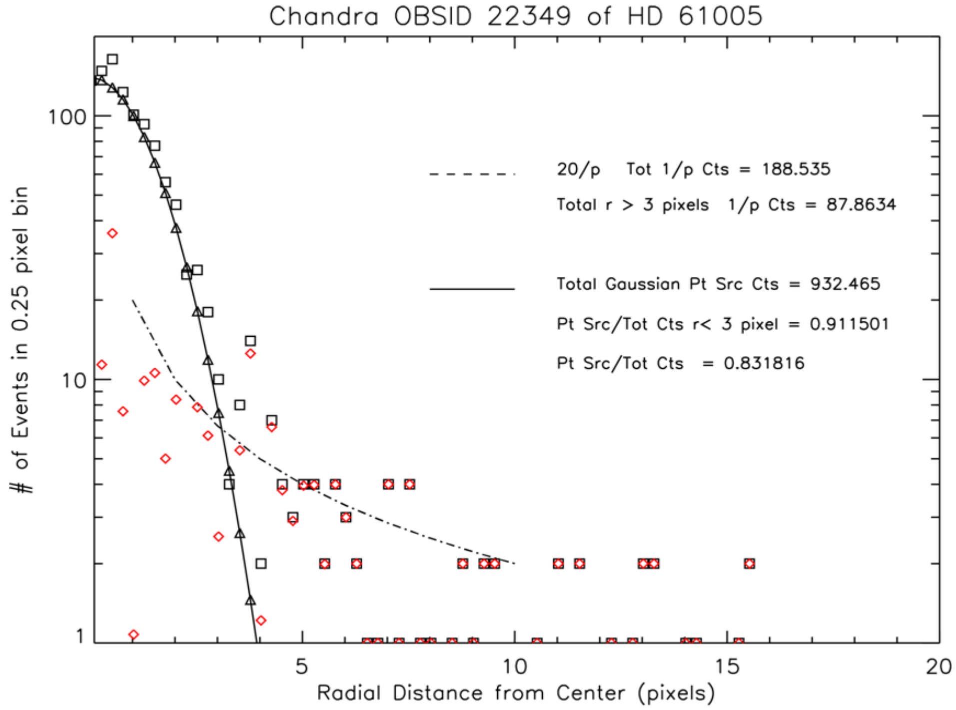
18 Sco, G2V, 4900 Myr, 14 pc

Beta Hyi, G2IV, 6700 Myr, 7.5 pc

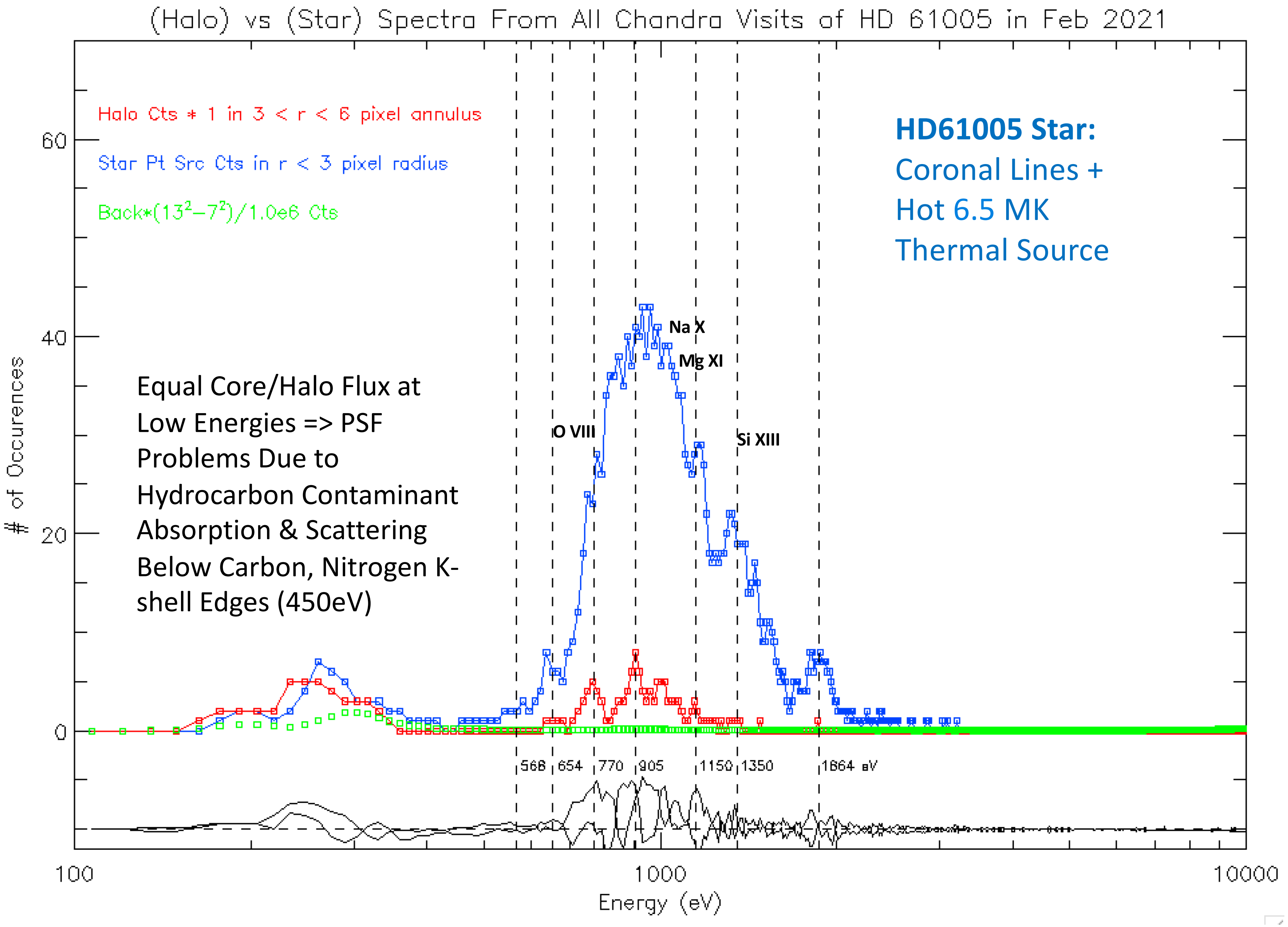
Tau Ceti, G8V, 5800 Myr, 3.7 pc



Chandra ACIS-S images of Beta Hyi and Tau Ceti vs HD61005, highlighting coronal and astrospheric components.

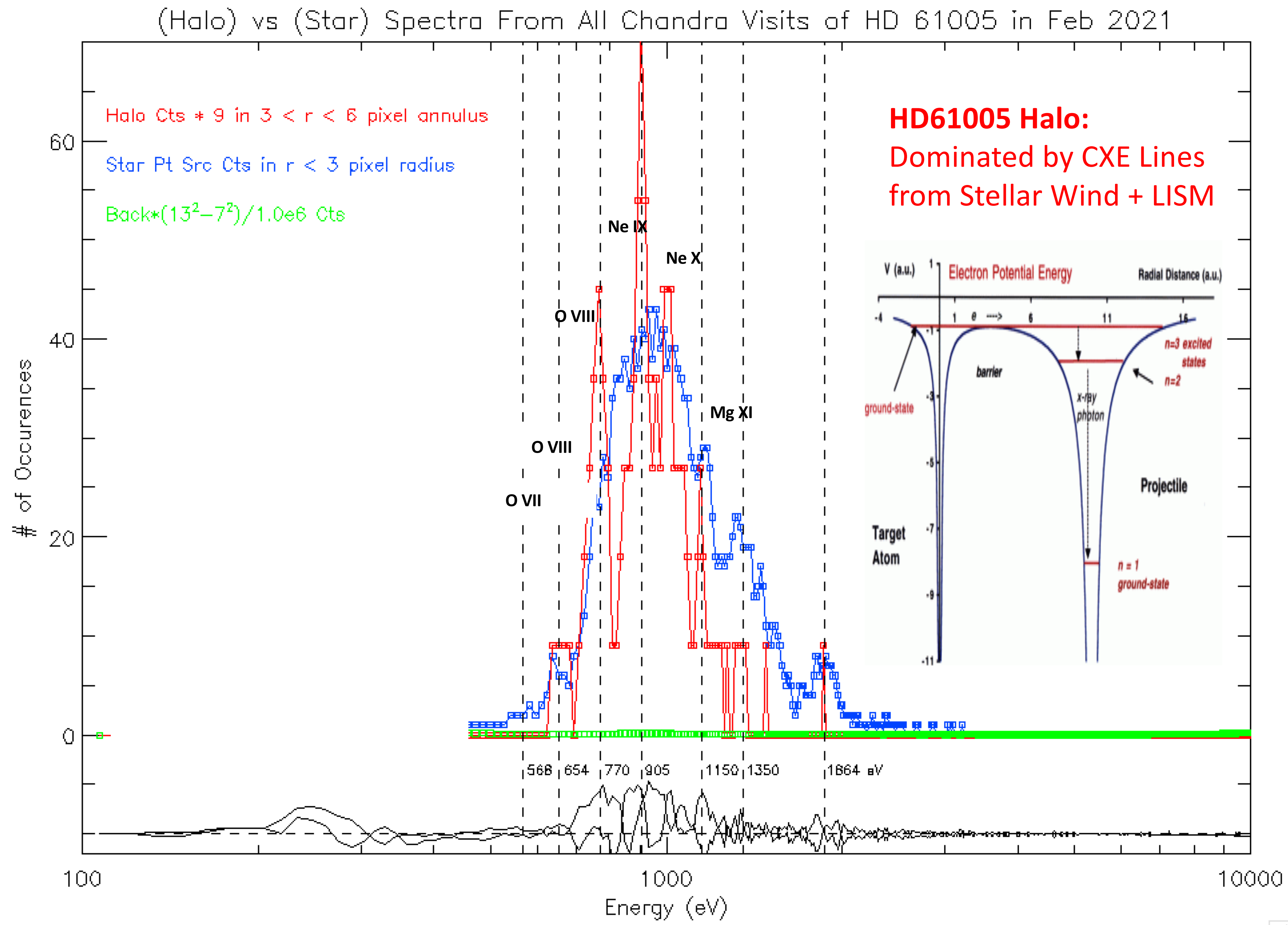


Chandra ACIS-S background-corrected radial aperture photometry. Two components are clearly seen: a Point-source (Stellar Corona) + 1/p Extended Source (Halo). Halo dominates at r > 3 pixels.



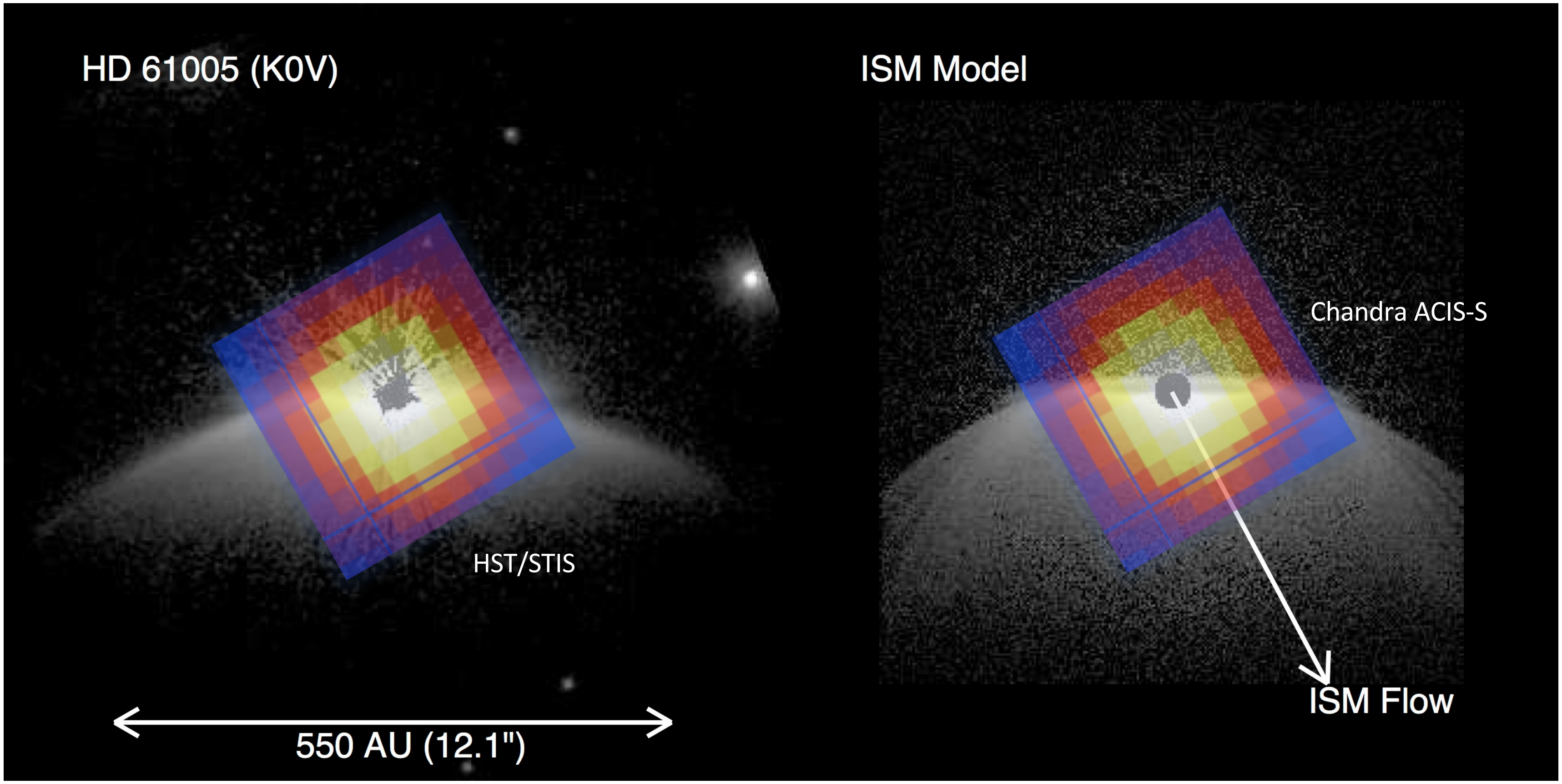
HD61005 Star:
Coronal Lines +
Hot 6.5 MK
Thermal Source

Equal Core/Halo Flux at Low Energies => PSF Problems Due to Hydrocarbon Contaminant Absorption & Scattering Below Carbon, Nitrogen K-shell Edges (450eV)



HD61005 Halo:
Dominated by CXE Lines from Stellar Wind + LISM

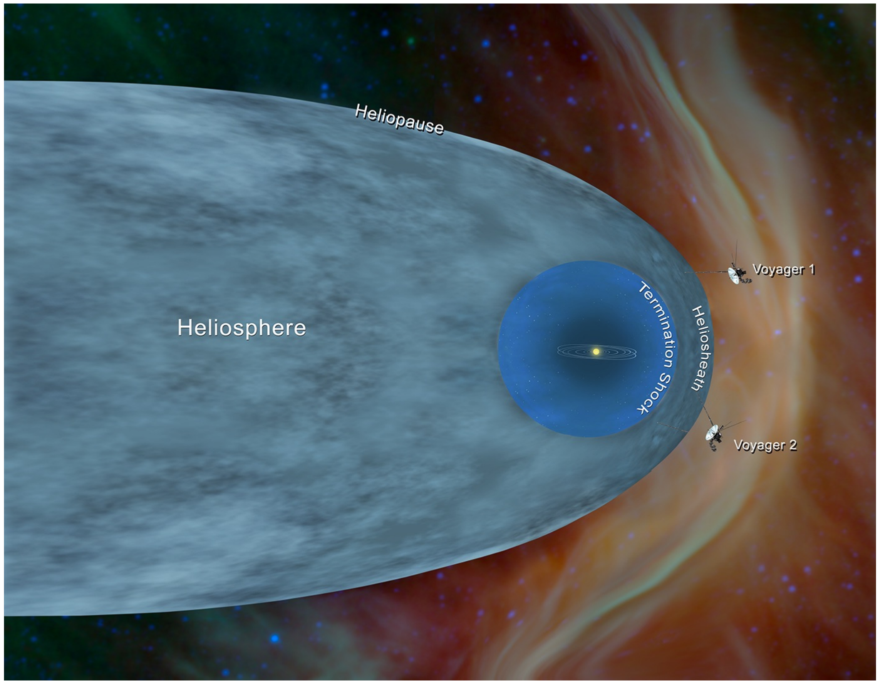
Overlay of the new Chandra imaging of HD61005 on* HST/NICMOS near-infrared imagery (*left*) and Debes+ 2009 model of the system's dust structure** (right)*** produced by invoking ISM wind ram pressure perturbations of circumstellar dust orbits.

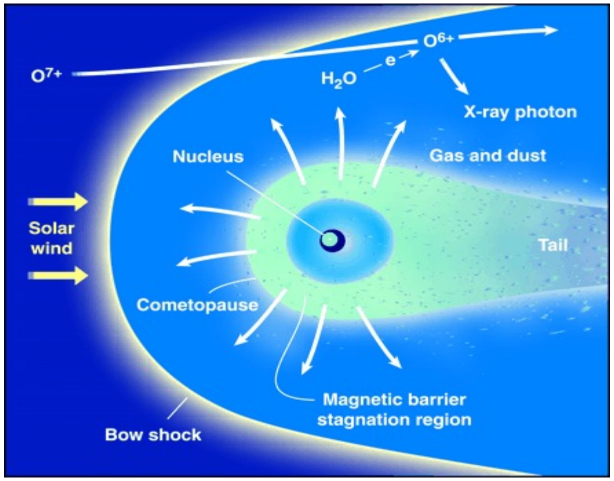


Noteworthy is the spherical symmetry of the x-ray emission, denoting an astrosphere morphology dominated by the strong stellar wind of the ~ 100 Myr old host G8V star; the ~100 au radial extent of the extended x-ray emission and the beginning of the NICMOS dust "wings" (f**or scale, Voyager 1 has found the heliopause in our L_x ~ $10^{27.5}$ system at ~120 AU), and the roots of the Wings at ~ the astropause distance.**

Simple Toy Model for HD61005 SW – VLISM Interaction

- Given **Pressure Balance** $n_{SW} * v_{SW}^2 = n_{ISM} * v_{ISM}^2$

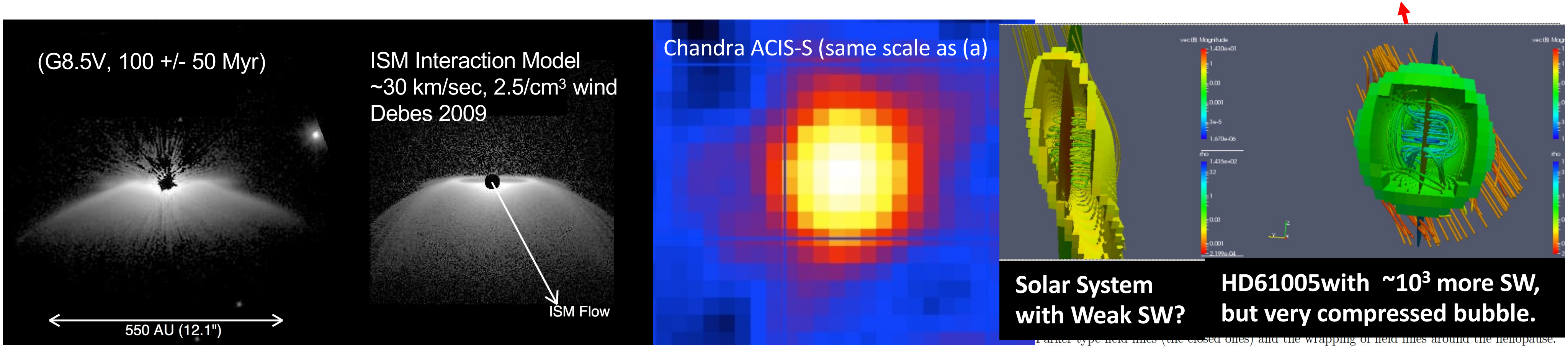




Given $\mathbf{L_{X,CXE}} \sim \sigma_{CXE} * n_{neutral} * n_{sw} (n_{minor}/n_H) * v_{sw} * \text{Volume}_{interaction} * \langle E_{photon} \rangle$

- Then, assuming $n_{sw} \sim 1/r^2$, $v_{ISM} = 25$ km/sec (Debes 2009), $(n_{minor}/n_H) \sim 10^{-3}$, and $V_{sw} \sim 1200$ km/sec for a young G9-star
- Including new Chandra finding constraints : $R_{astrosphere} \sim 100$ au and $L_{X,CXE} \sim 1.3 \times 10^{29}$ erg/sec
- => We find $\mathbf{n_{VLISM} = 100 – 300/cm^3}$ **(~1000x $\mathbf{n_{VLISM,\ Sun}}$)** and $\mathbf{n_{SW} \sim 2000/cm^3}$ **at 1 AU from host star (~$\mathbf{10^3}$ solar)**

Conclusions for Chandra ACIS-S Imaging of HD61005



- The stellar XUV activity and wind for HD61005 should be hot & high, about that observed by Guinan *et al.* for EK Dra, as HD61005 has an ~5 day stellar rotation rate. => We find an ~7 MK corona **> 200x more XUV active than the ~1 MK. ~4.5 Gyr old Sun or 6-7 Gyr G8V Tau Ceti**.

- X-ray emission is extended out to ~100 au, with a pronounced "Halo" not found in other point-source G-star observations. The halo's x-ray spectrum is CXE line dominated, like our heliosphere's.

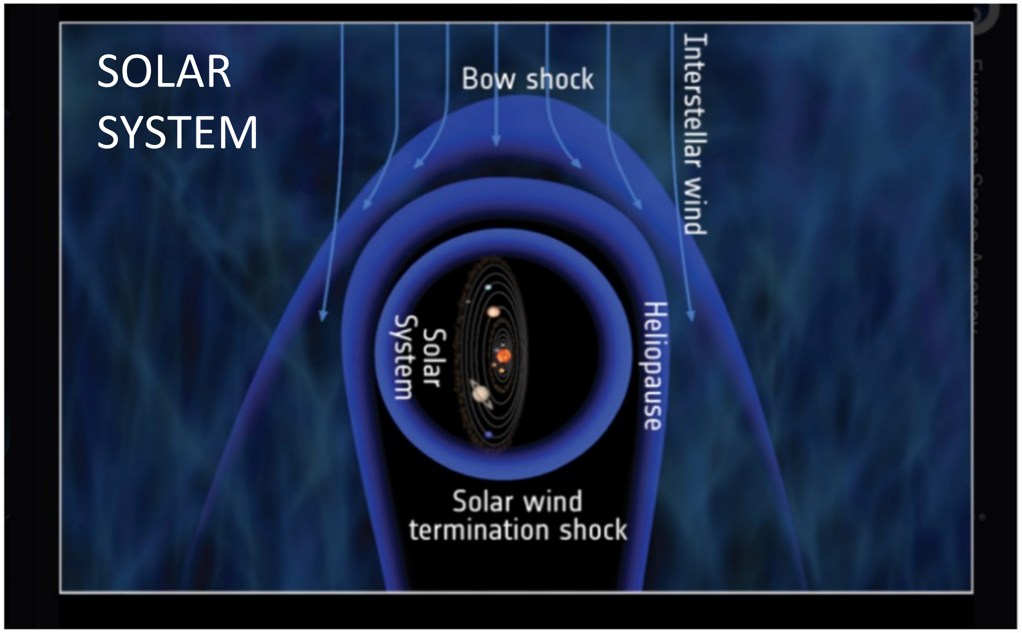
- HD61005' **local ISM must be very dense** in order for a system with $L_x \sim 10^2 F_{SW,\,Sun}$ to have **an astropause at only ~100 au**. => $\rho_{ISM,\,HD61005} = 100 - 300/cm^3$ using simple pressure balance, densities found inside GMC's like the Local Lynx Cloud (LLC).

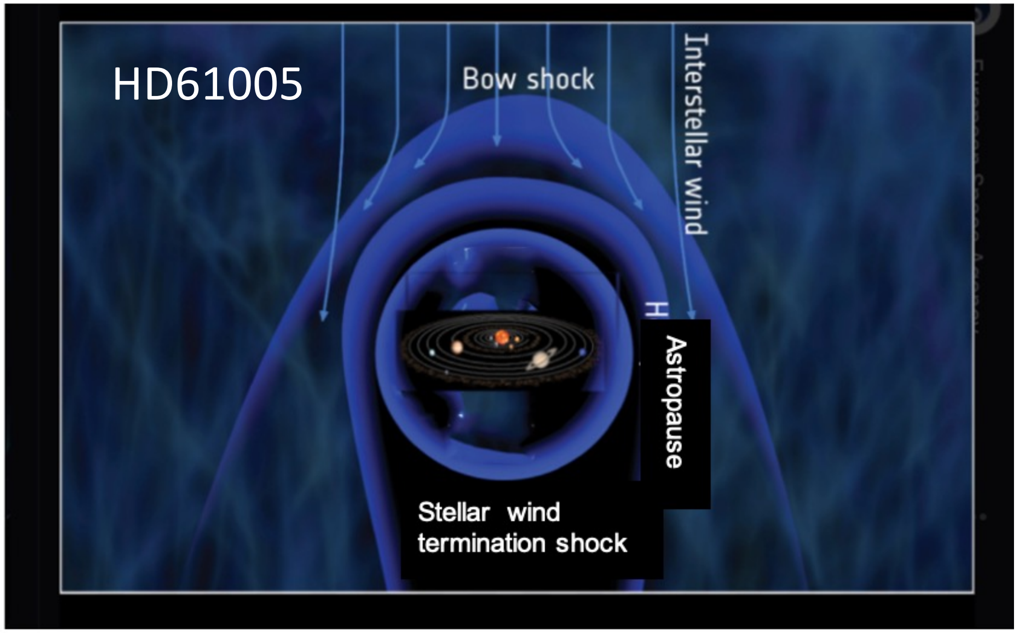
[The solar system system **TODAY** has $\rho_{VLISM,\,Sun} = 0.2/cm^3$ and heliopause at ~120 AU, but would have a heliopause at ~ 1000 au if the SW was 100x stronger].

- 1st ever spatially resolved G-star astrosphere: Due to **its youth** and its **dense VLISM, HD61005's CXE emission measure** $n_{sw} * v_{sw} * n_{ISM} \sim 10^6 * n_{sw,Sun} * v_{sw,Sun} * n_{ISM,\,Sun}$.

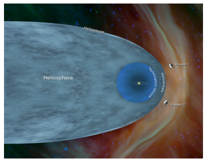
- **The resolved Halo does NOT appear to follow the well known disk + fan tail and appears spherical in nature.** This argues that the stellar wind – VLISM interaction is Parker stellar wind dominated.

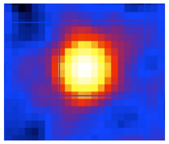
Open Questions: HD61005 Needs Full-Up Heliosphere Modeling (e.g., ”Face-On ISM RAM” Geometry)





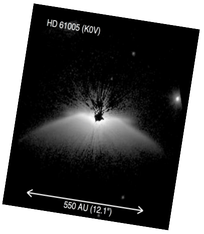
Solar System Evolution: At r ~ 100 au, HD61005’s astrosphere is smaller than our own (r ~ 120)! => When HD61005 moves into “normal” ISM space, its astrosphere will balloon up to r ~ 1000 au (& ours will shrink down to r ~ 2-5 au when we move into its cloud as we orbit the galactic center!) (Opher *et al.* 2023, 2024)



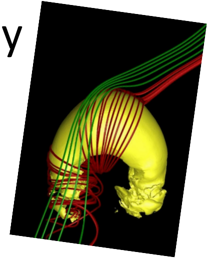


Search for Other Young G-star Disk Systems? Nearby, edge-on HD 107146 and HD 202917 seem promising.

Is There Hope for an Alpha Cen CXE Astrosphere Detection With NextGen X-ray Telescopes? n_{sw} $*v_{sw}*n_{vlism}/d^2 = 10^2 – 10^3$ in solar units for HD61005 & ~1 for Alpha Cen. So probably not…Procyon?



The “Wings” - are the “swept-back, fine particle” wings due to disk dust blowout, ISM sputtering of unprotected dust, or by exclusion of ISM neutrals? Are they coincident with the prongs of the croissant in the Boston groups models?



If you liked this talk…
look for our 2024 paper!!

First Detection of a Resolved Astrosphere Around a Main Sequence G-Star by Chandra

C.M. Lisse[1], S.J. Wolk[2], B. Snios[2], J.D. Slavin[2], R.A. Osten[3], D.C Hines[3], J.H. Debes[3], D. Koutroumpa[4], V. Kharchenko[2], M.A. MacGregor[5], J.L. Linsky[5], H.M. Günther [6], E.F. Guinan[7], S. Redfield[8], P.C. Frisch[9], K. Dennerl[10], V. Kashyap[2], K.G. Kislyakova[11], Y.R. Fernandez[12], E. Provornikova[1], C.H. Chen[3], R.L. McNutt[1], P. Brandt[1], L. Paxton[1], M. Horanyi[5]

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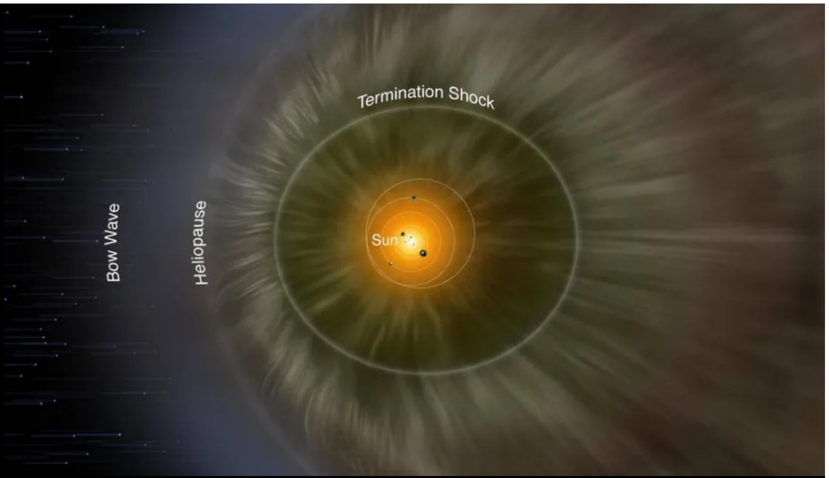
39 Pages, 10 Figures, 0 Tables

Key words: X-rays: stars; techniques: spectroscopic; stars: planetary systems: formation, debris disks; astrochemistry

Supplementary Slides

Some Calculations of the Scale of the SW



Pressure of the Heliosphere:

PV = nkT or P = (n/V) kT and
[760 torr = 1 atm = 1.01 x 10^5 Pa, => 1 torr = 133 Pa, 1 Pa = 1/133 torr]

So for Density ~ 1 H/cm^3 at 1million K Temperature, we have
P = (1 H/cm^3 * 10^6 cm^3/m^3) *1.38x10^{-23}*10^6 deg K = **1.4 x 10^{-11} Pa [or ~ 1x10^{-13} torr]**

By comparison: Fluorescent light bulb Hg plasma pressure ~ 0.8 Pa = 6 x 10^{-3} torr
Good rough pump vacuum ~ 1 x 10^{-3} torr = 1.3 x 10^{-1} Pa
Good turbopump vacuum ~ 1 x 10^{-7} torr = 1.3 x 10^{-5} Pa= Pressure on Pluto's surface, 10x Pressure in a Fusion Reactor
Ultra High Lab Vacuum = 1 x 10^{-10} to 1 x 10^{-11} torr = 1.3 x 10^{-8} Pa to 1.3 x 10^{-9} Pa

Mass of the Heliosphere:

4π/3 *<1 H/cm^3 > * (1.67 x 10^{-24} g/H-atom) * (1.5 x 10^{13} cm$)^3$ = 24 x 10^{15} g = **2.4e13 kg**
2.4 x 10^{13} kg is the mass of a 2.3 km radius comet of 0.5 g/cm^3 density

Mass Flux into the Heliosphere:

Sun loses ~2 x 10^{-14} M_{Sun}/yr =2 x 10^{-14}/yr * 2 x 10^{30} kg * /(3.1 x 10^7sec/yr) = 1.3 x 109 kg/sec
4 H/cm^3 at 1 AU * (1.67 x 10^{-27} kg/H atom) * 4π*(1.5 x 10^{13} cm/AU$)^3$ * 450 x 10^5cm/sec = **1.3 x 10^9 kg/sec**
1 x 10^9 kg is the mass of a large comet's coma, or of an 100 m radius comet-like body, or 500 Olympic swimming pools

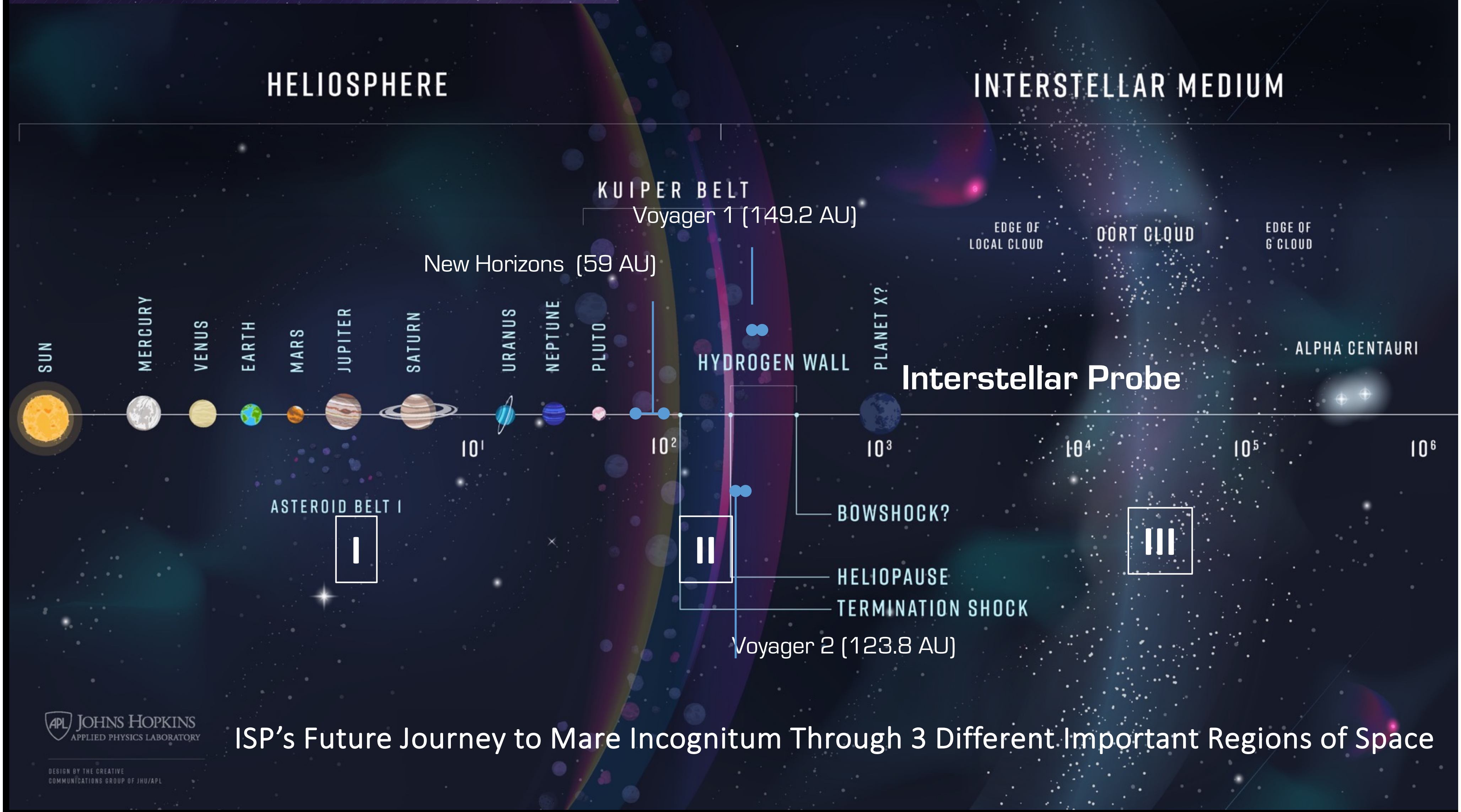
Sun masses 3.3 x 10^5 M_{Earth}, so Sun loses 7 x 10^{-8} M_{Earth}/yr, 70% of M_{earth} in 10 Myrs, ~300 M_{earth} in 4.56 Gyr, the age of the solar system (at current rates; the Sun's stellar wind was hundreds of times stronger when it was first born). Stellar winds from of low-mass stars likes the Sun do not strongly influence their evolution on THE MAIN SEQUENCE. (Pre- and Post-Main Sequence Stellar Winds CAN cause ~M_{Sun} mass losses in Myrs!)

HUMANITY'S JOURNEY TO INTERSTELLAR SPACE

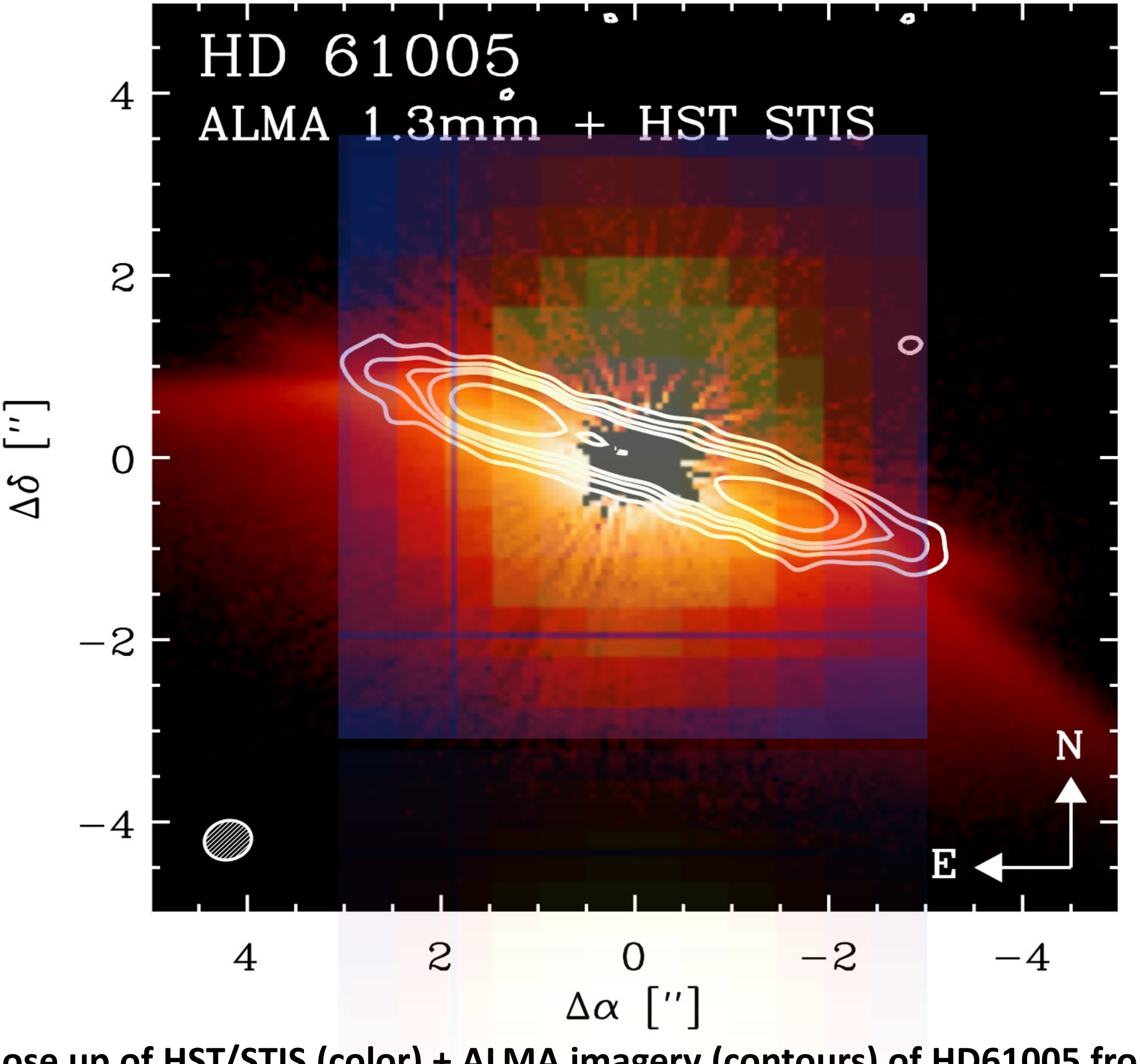
INTERSTELLAR

PROBE

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY



ISP's Future Journey to Mare Incognitum Through 3 Different Important Regions of Space



ALMA + STIS + Chandra ACIS-S Imaging of HD61005
(w/ ACIS-S at same scale & coord as ALMA + STIS).

The Chandra x-rays extend to the base of the Moth's "Wings".

Close up of HST/STIS (color) + ALMA imagery (contours) of HD61005 from MacGregor+ (2018), which suggest that there are two components to the disk populated by both small micron-sized grains (HST) and larger mm-sized grains (ALMA): (1) a confined planetesimal belt between 42 and 67 AU with a rising surface density gradient and (2) an extended outer halo interacting with and swept-back by the VLISM. **For scale, Voyager 1 has found the heliopause in our L_x ~ $10^{27.5}$ system at ~150 AU. (right) HD61005: Chandra ACIS imagery is an ~10 pixels wide blob. For 0.5" x 0.5" pixels, this is a spherical blob about 5" in diameter, or 5" * 35 pc * 1AU/pc = 175 au across.**

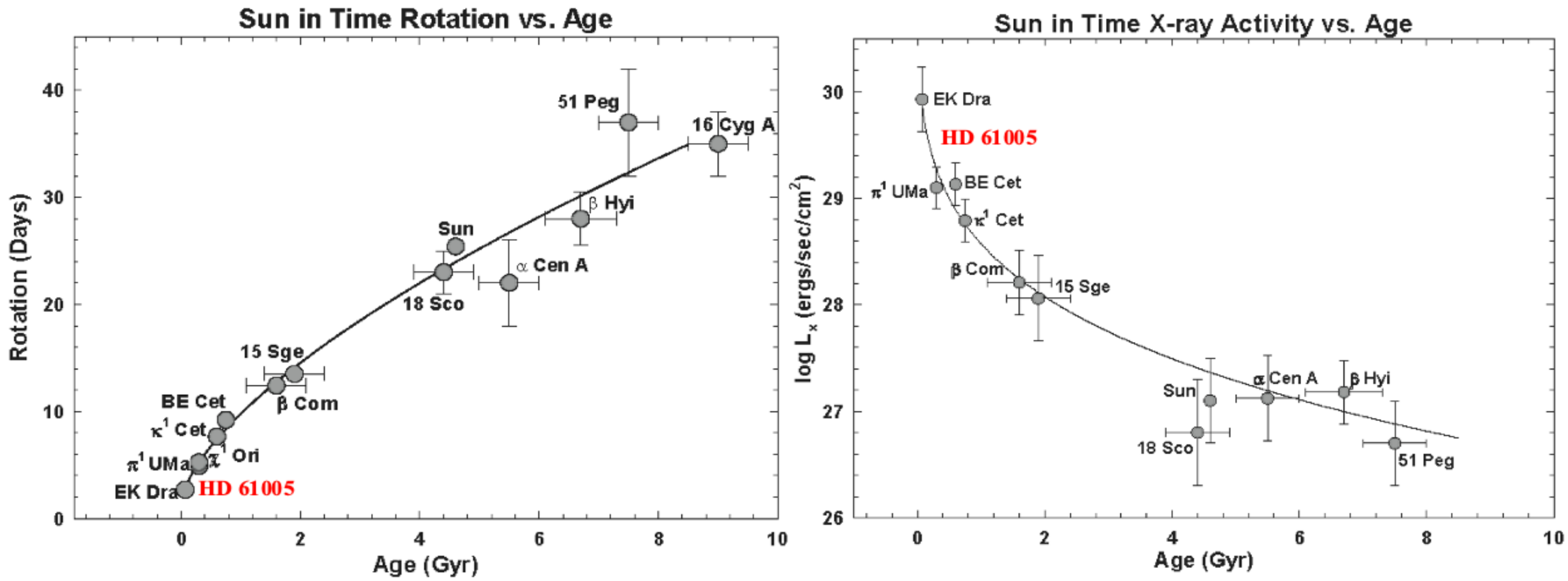


Figure 3(d) – Measured rotation rate vs stellar age for the Sun and several close solar analogues. The solid curve is a simple power law fit modeling $P_{rot} \sim Age^{0.6}$. **Figure 3(e) – As measured XUV luminosities for EK Dra, π^1 Uma, π^1 Ceti, Beta Com,** and **Beta Hyi,** ***all close solar analogue stars*****.** Notice the factor of $\sim 10^3$ higher flux between EK Dra (=HD 61005) and β Hyi (= Tau Ceti). After Guinan & Engle (2007).

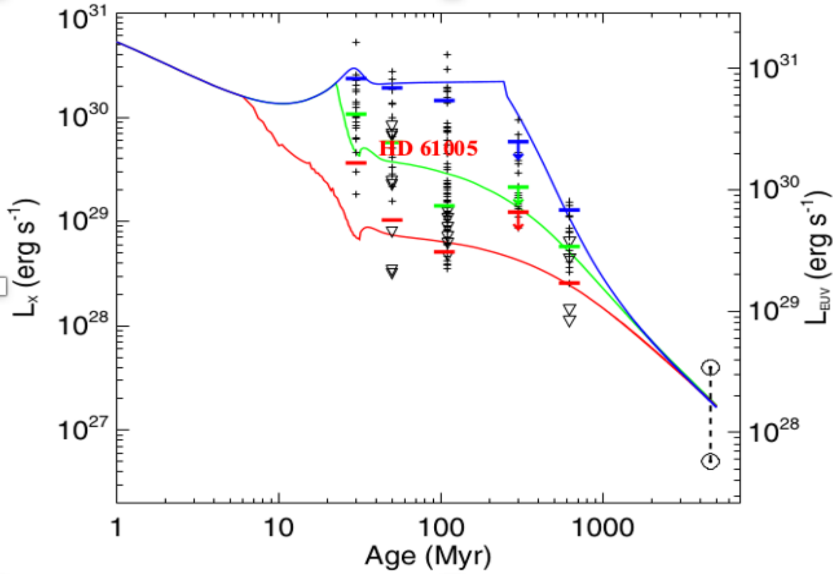
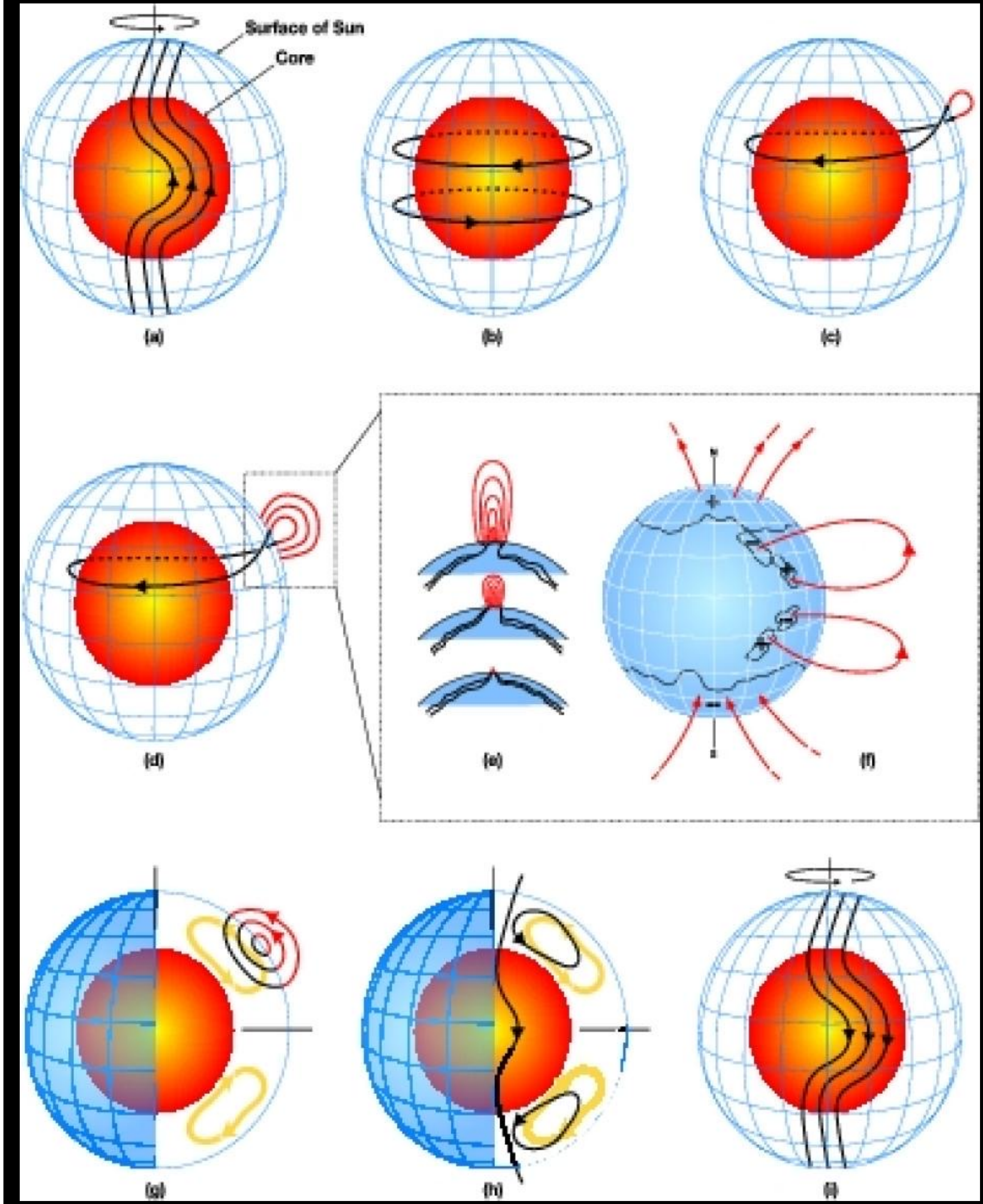
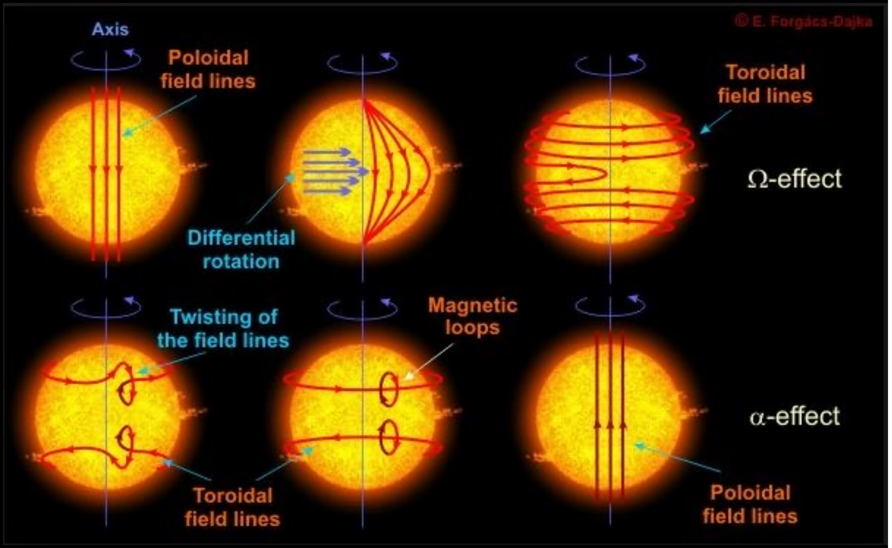
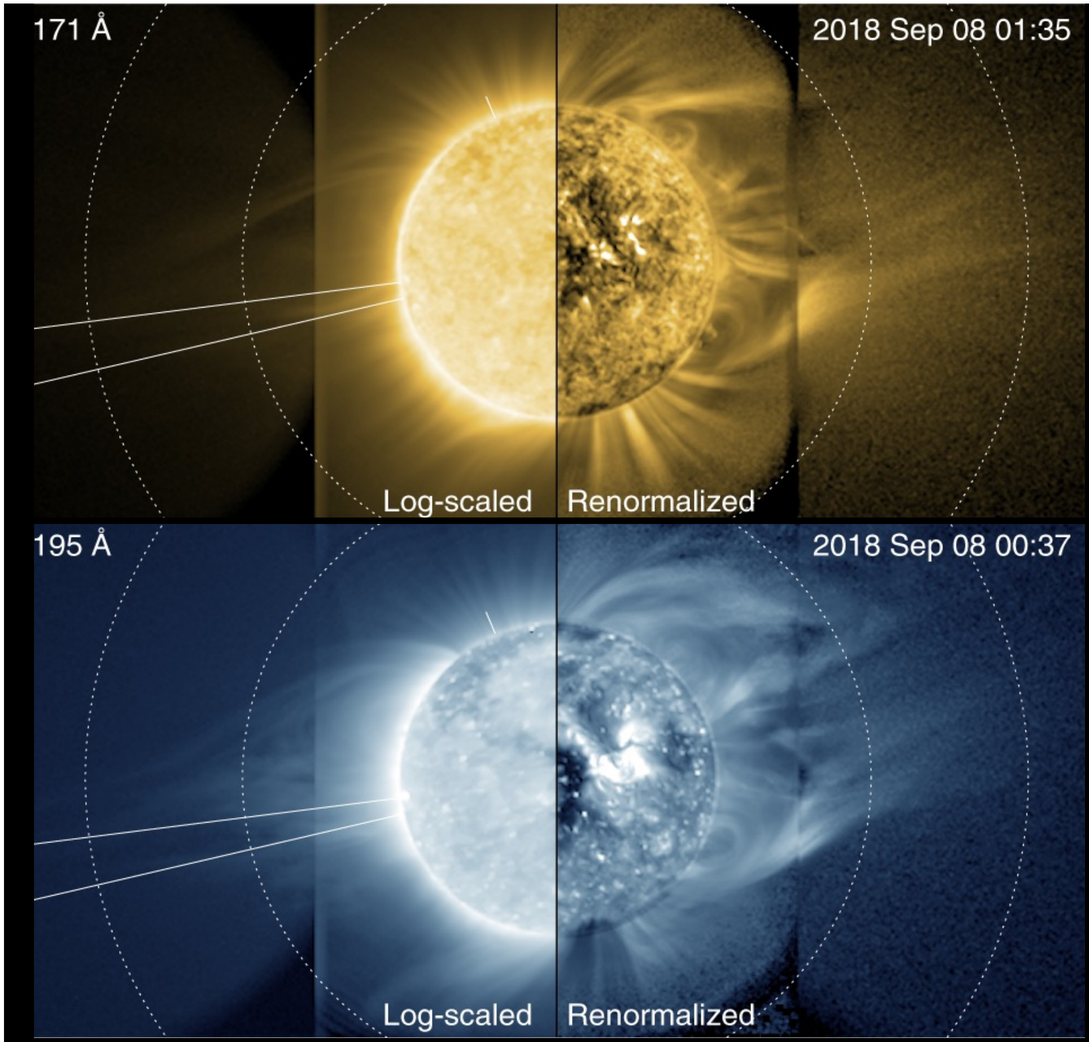


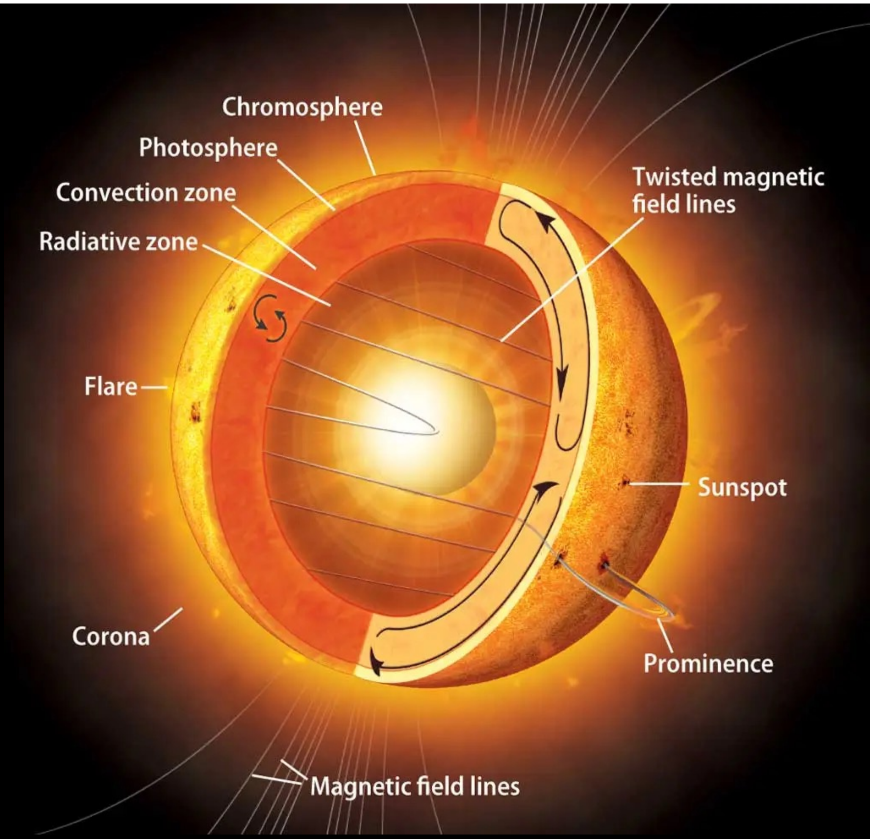
Figure 3(f) – Update of the L_x vs Age plot including an order of magnitude more G-stars and the predicted low (red), median (green) and high (blue) cases. After Tu *et al.* 2015.



Twisting of Magnetic Field Lines as the Sun Differentially Rotates Heats the Solar Coronal Atmosphere to ~1 MK (versus the 5780K surface temperature of the Sun) and powers the Solar Wind.







Stellar Wind (SW) = A flow of gas ejected from the upper atmosphere of a star. G-type stars like the Sun have a wind driven by their hot, magnetized coronae. The Sun's wind is called the solar wind. These winds consist mostly of high-energy (~ keV), fast (200-800 km/sec, or ~0.1% light speed) stream of mostly ionized hydrogen, helium, and electrons (>99%) that are able to escape the star's gravity because of the high temperature of the corona.