Blowing Bubbles in the Galaxy: Chandra Detects the 1st Ever Resolved Atmosphere 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

Carey Lisse, Meredith MacGregor, E. Provornikova, Pontus Brandt, Ralph McNutt, Larry Paxton (JHU-APL), Scott Wolk, Brad Snios, V. Kashyap (CXC/Harvard-SA0), H.M. Gunther (MIT), K. Dennerl (MPE), K.G. Kislyakova (Vienna), Dean Hines, Christine Chen, John Debes (STScI), Seth Redfield (Weslyan), Jeff Linsky, Mihalyi Horanyi (CU), Priscilla Frisch (UChicago), Jon Slavin (Harvard-SA0), E.F. Guinan (Villanova), Y.R. Fernandez (UCF) CXUniverse 18 June 2024

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

New Chandra HD61005 X-ray Spectral Imaging of Extended Atmosphere + Star
(Lisse+ 2024)
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 on its orbit around the Galactic Center ($v_{\text{rel}} \sim 230$ km/sec, $P_{\text{rot}} \sim 250$ Myr).
Detecting Astrospheres Around Mid-Life, Main Sequence Stars Like the Sun is Hard!

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

\[ n_{SW} \times v_{SW}^2 = n_{ISM} \times v_{ISM}^2 + B_{ISM}^2/4\pi + P_{ISM,\text{thermal}}, \text{found, with cavity radius } \sim 10^2 \text{ AU}, \]

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

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

Great 08-Apr-2024 North American Solar Eclipse Directly Revealed the Actinic Light from Our Sun’s MK Corona.
Enter **HD61005** (aka THE MOTH)! A system harboring a Circumstellar Disk with Marked Structure due to ISM-Disk Interactions.

(G8.5V, 40 – 130 Myr)

ISM Interaction Model Debes 2009

$v_{\text{ISM}} \sim 30 \text{ km/sec}$

$n_{\text{ISM}} \sim 25/\text{cm}^3 \text{ wind}$

**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).

HD61005: G9V
Mass = ~0.9 $M_{\text{sun}}$
Luminosity = 0.6 $L_{\text{sun}}$
Radius = 0.86 $R_{\text{sun}}$
$T_{\text{eff}}$ = 5480 K
Age = 50 - 100 Myr old
$P_{\text{rot}}$ ~ 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 ~ 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 than 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.
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)
(Halo) vs (Star) Spectra From All Chandra Visits of HD 61005 in Feb 2021

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

Halo Cts * 9 in $3 < r < 6$ pixel annulus
Star Pt Src Cts in $r < 3$ pixel radius
Back $(13^2 - 7^2) / 1.0e6$ Cts
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” (for scale, Voyager 1 has found the heliopause in our \( L_x \sim 10^{27.5} \) 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** \( n_{SW} \times v_{SW}^2 = n_{ISM} \times v_{ISM}^2 \)

- Then, assuming \( n_{sw} \sim 1/r^2 \), \( v_{ISM} = 25 \text{ km/sec} \) (Debes 2009), \( (n_{\text{minor}}/n_H) \sim 10^{-3} \), and \( V_{sw} \sim 1200 \text{ km/sec} \) for a young G9-star

- Including new Chandra finding constraints: \( R_{\text{astrosphere}} \sim 100 \text{ au} \) and \( L_{X,CXE} \sim 1.3 \times 10^{29} \text{ erg/sec} \)

- => We find \( n_{VLISM} = 100 - 300/\text{cm}^3 \) (\( \sim 1000 \times n_{VLISM,\ Sun} \)) and \( n_{SW} \sim 2000/\text{cm}^3 \) at 1 AU from host star (\( \sim 10^3 \text{ solar} \))
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.

CXUniverse 18 June 2024
**Open Questions:** HD61005 Needs Full-Up Heliosphere Modeling (e.g., “Face-On ISM RAM” Geometry)

**Solar System Evolution:** At $r \sim 100$ au, HD61005’s astrosphere is smaller than our own ($r \sim 120$)! => When HD61005 moves into “normal” ISM space, its astrosphere will balloon up to $r \sim 1000$ au (& ours will shrink down to $r \sim 2$-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 CXF Astrosphere Detection With NextGen X-ray Telescopes?**

$n_{sw} \times v_{sw} \times n_{vlism} / d^2 = 10^2 \sim 10^3$ 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?
First Detection of a Resolved Atmosphere Around a Main Sequence G-Star by Chandra

C.M. Lisse¹, S.J. Wolk², B. Snios², J.D. Slavin², R.A. Osten³, D.C Hines³, J.H. Debes³, D. Koutoumpa⁴, V. Kharchenko⁵, M.A. MacGregor⁶, J.L. Linsky⁶, H.M. Günther⁷, E.F. Guinan⁷, S. Redfield⁸, P.C. Frisch⁹, K. Dennerl¹⁰, V. Kashyap¹, K.G. Kislyakova¹¹, Y.R. Fernandez¹², E. Provornikova¹, C.H. Chen³, R.L. McNutt¹, P. Brandt¹, L. Paxton¹, M. Horanyi¹

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

In preparation for submission to Astrophysical Journal 08-March-2024

¹Planetary Exploration Group, Space Department, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd, Laurel, MD 20723 carey.lisse@jhuapl.edu, ralph.mcnett@jhuapl.edu, pontus.brandt@jhuapl.edu
²Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, 02138 swolk@cfa.harvard.edu, vkharchenko@cfa.harvard.edu, bradford.snios@cfa.harvard.edu, jlsavin@cfa.harvard.edu
³Space Telescope Science Institute, 3700 San Martin Dr. Baltimore, MD 21218 osten@stsci.edu, john.debes@gmail.com, hines@stsci.edu, echen@stsci.edu
⁴Laboratoire Atmosphères, Observations Spatiales, 78280 Guyancourt, France Dimitra.Koutoumpa@atmos.ipsl.fr
⁵University of Colorado, Boulder CO Meredith.MacGregor@colorado.edu, j.linsky@jila.colorado.edu, mihaly.horanyi@lasp.colorado.edu
⁶Massachusetts Institute of Technology, Kavli Institute for Astrophysics and Space Research, 77 Massachusetts Avenue, NE83-569, Cambridge, MA 02139 hgunther@mit.edu
⁷Villanova University, Dept. of Astrophysics and Planetary Sci, 800 Lancaster Avenue, Villanova, PA 19085 edward.guinan@villanova.edu
⁸Wesleyan University, Astronomy Department, 96 Foss Hill Drive, Van Vleck Observatory 101, Middletown, CT 06459 sredfield@wesleyan.edu
⁹University of Chicago, Department of Astronomy and Astrophysics, 5640 S. Ellis Ave, Chicago, IL 60637 pfrisch@hep.uchicago.edu
¹⁰Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, Giessenbachstraße, D-85741 Garching, Germany kod@mpe.mpg.de
¹¹Department of Astrophysics, University of Vienna, Tuerkenschanzstrasse 17, Wien, Austria A-1180 kristina.kislyakova@univie.ac.at
¹²Department of Physics, University of Central Florida, Orlando, FL 32816 yan@physics.ucf.edu

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:**

\[ PV = nkT \text{ or } P = (n/V)kT \]

\[ [760 \text{ torr} = 1 \text{ atm} = 1.01 \times 10^5 \text{ Pa}, \Rightarrow 1 \text{ torr} = 133 \text{ Pa}, 1 \text{ Pa} = 1/133 \text{ torr}] \]

So for \( \text{Density} \sim 1 \text{ H/cm}^3 \) at 1 million K Temperature, we have

\[ P = (1 \text{ H/cm}^3 \times 10^6 \text{ cm}^3/\text{m}^3) \times 1.38 \times 10^{-23} \times 10^6 \text{ deg K} = 1.4 \times 10^{-11} \text{ Pa} \text{ [or } \sim 1 \times 10^{-13} \text{ torr}] \]

By comparison: Fluorescent light bulb Hg plasma pressure \( \sim 0.8 \text{ Pa} = 6 \times 10^{-3} \text{ torr} \)

Good rough pump vacuum \( \sim 1 \times 10^{-3} \text{ torr} = 1.3 \times 10^{-1} \text{ Pa} \)

Good turbopump vacuum \( \sim 1 \times 10^{-7} \text{ torr} = 1.3 \times 10^{-5} \text{ Pa} \)

Pressure on Pluto’s surface, 10x Pressure in a Fusion Reactor

Ultra High Lab Vacuum \( = 1 \times 10^{-10} \text{ to } 1 \times 10^{-11} \text{ torr} = 1.3 \times 10^{-8} \text{ Pa} \) to \( 1.3 \times 10^{-9} \text{ Pa} \)

**Mass of the Heliosphere:**

\[ 4\pi/3 \times <1 \text{ H/cm}^3> \times (1.67 \times 10^{-24} \text{ g/H-atom}) \times (1.5 \times 10^{13} \text{ cm})^3 = 24 \times 10^{15} \text{ g} = 2.4e13 \text{ kg} \]

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 \( \sim 2 \times 10^{-14} \text{ M}_\text{Sun}/\text{yr} = 2 \times 10^{-14}/\text{yr} \times 2 \times 10^{30} \text{ kg} / (3.1 \times 10^7 \text{ sec/yr}) = 1.3 \times 109 \text{ kg/sec} \)

4 H/cm\(^3\) at 1 AU \( \times (1.67 \times 10^{-27} \text{ kg/H atom}) \times 4\pi \times (1.5 \times 10^{13} \text{ cm}/\text{AU})^3 \times 450 \times 10^5 \text{ cm/sec} = 1.3 \times 10^9 \text{ kg/sec} \)

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\(_\text{Earth}\), so Sun loses 7 x 10\(^{-8}\) M\(_\text{Earth}/\text{yr}\), 70% of M\(_\text{Earth}\) in 10 Myrs, \( \sim 300 \text{ M}_{\text{Earth}} \) 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 \( \sim \text{M}_\text{Sun} \) mass losses in Myrs!)
ISP’s Future Journey to Mare Incognitum Through 3 Different Important Regions of Space
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 $L_x \sim 10^{27.5}$ system at $\sim 150$ AU. (right) HD61005: Chandra ACIS imagery is an $\sim 10$ 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, π1 Uma, π1 Ceti, Beta Com, and Beta Hvi, all close solar analogue stars. Notice the factor of $\sim 10^3$ higher flux between EK Dra (=HD 61005) and β Hvi (= 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.